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OCS Study
MMS 90-0088

California, Oregon, and Washington Archaeological Resource Study

Volume II: Geology

Project Editors

Robert L. Gearhart II
Clell L. Bond
Steven D. Hoyt

Volume II Authors

James Anderson
Kim Marcus
Jerry Wilson, Ph.D.

Prepared under MMS Contract
14-35-0001-30439
by
Espey, Huston & Associates, Inc.
P.O. Box 519
Austin, Texas 78767

Subcontractor:
Dames & Moore
San Diego, California

Published by

U.S. Department of the Interior
Minerals Management Service
Pacific OCS Region

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ABSTRACT

In May 1989, the Pacific OCS Region of MMS contracted with Espey, Huston & Associates, Inc. (EH&A) of Austin, Texas to conduct a study of the OCS between Morro Bay, California and the Canadian Border. Overviews are presented for late Pleistocene/Holocene geology of the OCS, for prehistory of the coastal zone, and for maritime history of the study area. Models are formulated to predict the areas in which prehistoric and historic archaeological sites are likely to be preserved on the OCS. Variables considered by these models include late Pleistocene and Holocene geology of the OCS, known archaeological site distributions, prehistoric settlement patterns, vessel traffic patterns, and the distribution of significant hazardous weather conditions. Holocene geology, known site distributions, and archaeological site predictive zones resulting from this project have been mapped at a scale of 1:250,000 and are bound as an atlas for inhouse use by MMS. Smaller scale copies of these maps, lacking specific locational information for archaeological sites, have been produced for public distribution. The results of this study will be used in evaluating exploration, development and transportation plans for mineral development activities on the OCS and in determining remote-sensing survey requirements that will apply to specific areas of the OCS.

TABLE OF CONTENTS

Section		Page
	Abstract	II-ii
	List of Figures	II-vi
	Acknowledgements	II-vii
1.0	**INTRODUCTION**	II-1
1.1	**Study Objectives**	II-1
1.2	**Study Area**	II-2
2.0	**REVIEW OF LATE PLEISTOCENE AND HOLOCENE GEOLOGIC HISTORY, MODERN CONTINENTAL SHELF, CLIMATOLOGY, AND SEA LEVEL FLUCTUATIONS**	II-4
2.1	**Late Pleistocene and Holocene History**	II-4
2.1.1	*Tectonic History*	II-4
2.1.2	*Holocene Transgression*	II-9
2.2	**Modern Continental Shelf**	II-11
2.2.1	*Geologic Control*	II-11
2.2.2	*Oceanic Control*	II-13
2.2.3	*Continental Shelf Sedimentation*	II-13
2.2.4	*Sedimentary Facies of the Continental Shelf*	II-18
2.2.5	*Generalized Morphology Description of the Continental Shelf of the Study Area*	II-18
2.3	**Late Pleistocene/Holocene Climatology**	II-19
2.3.1	*Pacific Northwest*	II-19
2.3.2	*California*	II-20
2.4	**Sea Level Fluctuations**	II-21
3.0	**PHYSICAL ENVIRONMENTS**	II-24
3.1	**Cape Flattery, Washington, to Heceta Head, Oregon (44°N)**	II-24
3.1.1	*Delineation of Area*	II-24
3.1.2	*Regional Setting*	II-24
3.1.2.1	Coastal Physiography	II-24
3.1.2.2	Tectonic History and Setting	II-26
3.1.2.3	Shelf Physiography	II-27
3.1.2.4	Geology	II-28
3.1.2.5	Oceanographic Setting	II-32
3.1.3	*Representative Late Pleistocene/Holocene Stratigraphy*	II-32
3.1.3.1	Late Pleistocene/Holocene Differentiation	II-33
3.1.3.2	Pleistocene Stratigraphy	II-33
3.1.3.3	Holocene Stratigraphy	II-34
3.1.4	*Sea Level Fluctuations*	II-36
3.1.5	*Holocene Sediment Isopach Maps*	II-39
3.1.6	*Specific Features Judged to Have the Greatest Potential for Prehistoric Occupation*	II-40
3.2	**Heceta Head, Oregon (44°N) to Cape Mendocino, California (40°N 30'N)**	II-43

TABLE OF CONTENTS (Cont'd)

Section		Page
3.2.1	*Delineation of Area*	II-43
3.2.2	*Regional Setting*	II-45
3.2.2.1	Coastal Physiography	II-45
3.2.2.2	Tectonic History and Setting	II-45
3.2.2.3	Shelf Physiography	II-47
3.2.2.4	Geology	II-48
3.2.2.5	Oceanographic Setting	II-51
3.2.3	*Representative Late Pleistocene/Holocene Stratigraphy*	II-53
3.2.3.1	Late Pleistocene/Holocene Differentiation	II-53
3.2.3.2	Pleistocene Stratigraphy	II-53
3.2.3.3	Holocene Stratigraphy	II-54
3.2.4	*Sea Level Fluctuations*	II-55
3.2.5	*Holocene Sediment Isopach Maps*	II-56
3.2.6	*Specific Features Judged to Have the Greatest Potential for Prehistoric Occupation*	II-57
3.3	**Cape Mendocino, California (40°30'N) to Morro Bay, California**	II-58
3.3.1	*Delineation of Area*	II-58
3.3.2	*Regional Setting*	II-58
3.3.2.1	Coastal Physiography	II-58
3.3.2.2	Tectonic History and Setting	II-60
3.3.2.3	Shelf Physiography	II-61
3.3.2.4	Geology	II-62
3.3.2.5	Oceanographic Setting	II-67
3.3.3	*Representative Late Pleistocene/Holocene Stratigraphy*	II-67
3.3.3.1	Late Pleistocene Differentiation	II-67
3.3.3.2	Pleistocene Stratigraphy	II-68
3.3.3.3	Holocene Stratigraphy	II-69
3.3.4	*Sea Level Fluctuations*	II-71
3.3.5	*Holocene Sediment Isopach Maps*	II-72
3.3.6	*Specific Features Judged to Have the Greatest Potential For Prehistoric Occupation*	II-73
3.4	**Greater San Francisco Bay Area**	II-75
3.4.1	*Delineation of Area*	II-75
3.4.2	*Regional Setting*	II-75
3.4.2.1	San Francisco Bay Physiography	II-75
3.4.2.2	Tectonic History and Setting	II-76
3.4.2.3	Geology	II-76
3.4.2.4	Oceanographic Setting	II-76
3.4.3	*Representative Late Pleistocene/Holocene Stratigraphy*	II-77
3.4.3.1	Late Pleistocene/Holocene Differentiation	II-77
3.4.3.2	Pleistocene Stratigraphy	II-77
3.4.3.3	Holocene Stratigraphy	II-78

TABLE OF CONTENTS (Concluded)

Section		Page
3.4.4	*Sea Level Fluctuations*	II-80
3.4.5	*Holocene Sediment Isopach Maps*	II-80
3.4.6	*Specific Features Judged to Have the Greatest Potential for Prehistoric Occupation*	II-81
4.0	**REFERENCES CITED**	II-82

APPENDICES (Bound Separately)

APPENDIX A - INDIVIDUALS AND ORGANIZATIONS CONTACTED
APPENDIX B - BIBLIOGRAPHIES
General
Geology
Prehistory
History
APPENDIX C - NOTICE TO LESSEES AND OPERATORS OF FEDERAL OIL AND GAS LEASES IN THE OUTER CONTINENTAL SHELF, PACIFIC AREA
APPENDIX D - MARITIME RESOURCES QUESTIONNAIRE AND SUMMARY OF RESPONSES
APPENDIX E - MMS SHIPWRECK DATABASE REFERENCE LIST
APPENDIX F - NEWSPAPERS OF THE STUDY REGION
APPENDIX G - SHIPWRECK DATABASE FIELDS, CODES AND STANDARD ABBREVIATIONS

LIST OF FIGURES

Figure		Page
II-1	Study Area for the California, Oregon and Washington Archaeological Resource Study	II-3
II-2	Late Quaternary Fluctuations of Sea Level	II-5
II-3	Schematic Illustration of Plate Tectonics and Formation of Collision and Trailing-Edge Coasts	II-6
II-4	Generalized Tectonic Map of U.S. West Coast	II-8
II-5	Diagrammatic Profile of Continental Terrace and Continental Rise	II-12
II-6	Characteristic Shelf Stratigraphy Resulting from Sedimentation Following a Rise in Sea Level	II-15
II-7	Conceptual Model of Suspended Material Transport Across the Continental Shelf	II-17
II-8	Sea Level Curves for the Past 2,000 Years Along the Southern California and Texas Continental Margins	II-23
II-9	Location Map of Cape Flattery, Washington, to Heceta Head, Oregon Portion of the Study Area	II-25
II-10	Location of Submarine Banks off Northern and Central Oregon Coast	II-29
II-11	Washington/Northern Oregon Surficial Sediment Data	II-30
II-12	Representative Holocene Stratigraphy Across Washington Continental Margin	II-35
II-13	Representative Sea Level Curves for the Pacific Northwest	II-37
II-14	Location Map of Heceta Head, Oregon to Cape Mendocino, California Portion of Study Area	II-44
II-15	Generalized Tectonic Map of Northern California	II-46
II-16	Klamath Mountains Location Map	II-50
II-17	Offshore Northern and Central California Basins	II-52
II-18	Location Map of Cape Mendocino, California to Morro Bay, California Portion of Study Area	II-59
II-19	Location of Franciscan Complex and Salinian Block Basements	II-63
II-20	Average Annual Discharge of Suspended Sediment from the Major Streams Between Point Conception and the Oregon Border	II-70
II-21	Holocene Sea Level Curve in the Vicinity of Southern San Francisco Bay	II-79

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This study was coordinated by Mr. Robert Gearhart, EH&A Senior Staff archaeologist, with the assistance of Mr. Clell Bond, EH&A Vice President and manager of EH&A's cultural resources group. Together, Mr. Gearhart and Mr. Bond were responsible for the organization, editing and final content of these six volumes. Editorial assistance was contributed by Mr. Steven Hoyt, EH&A staff archaeologist. Principal Investigators for this study were: Mr. Robert Gearhart (responsible for historic and marine archaeology); Dr. Pandora Snethkamp (D&M archaeologist responsible for California prehistory); Dr. Gary Wessen (D&M archaeologist responsible for Washington and Oregon prehistory); and Mr. Kim Marcus (D&M geologist responsible for geology). Contributing authors, in alphabetical order, include: Mr. Jim Anderson (D&M geologist); Dr. James Cleland (D&M archaeologist); Mr. Robert Gearhart; Mr. Steven Hoyt; Mr. Kim Marcus; Mr. John Neville (EH&A archaeologist); Dr. Pandora Snethkamp; Dr. Gary Wessen; Dr. Jerry Wilson (D&M geologist); and Mr. Andrew York (D&M archaeologist). All work performed by D&M for this study was conducted under the supervision of Dr. James Cleland, a senior member of D&M's archaeological staff.

This report was critically reviewed by a Quality Review Board consisting of experts in geology, Pacific coast prehistory and marine archaeology. Our thanks to Dr. Curt Peterson (marine geologist and Assistant Professor with Portland State University), Dr. Lee Lyman (Northwest Coast prehistorian and faculty with the University of Missouri, Columbia), and Mr. J. Barto Arnold III (marine archaeologist with the State of Texas) for serving on the review board.

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1.0 INTRODUCTION

Study Objectives

The Minerals Management Service (MMS) is charged with the responsibility of ecting archaeological resources on the Outer Continental Shelf (OCS) from adverse impacts iated with mineral exploitation activities. In order to fulfill this reponsibility, MMS must first ify the archaeological resources which could be affected within a planning area.

The primary purpose of this study has been to identify areas of high versus low ability for the occurrence of significant archaeological resources on the OCS. This information hen be used by the MMS for lease sale and development planning.

In order to distinguish those areas of high versus low occurrence probability, a ictive model for prehistoric and historic site locations on the OCS has been developed. One e input parameters of the predictive model is the late Pleistocene/Holocene geology of the al zone and OCS.

The task of supplying a comprehensive review of the late Pleistocene/Holocene ogy of the coastal zone and OCS was accomplished through literature and data search, isition, and synthesis. An exhaustive search of pertinent literature and data sources and sitories was conducted resulting in a comprehensive baseline summary of the OCS and coastal geology, as well as drawing together available data on Holocene sediment deposits on the .

A great deal of geologic data are available for the southern California OCS study haeological Resource Study: Morro Bay to Mexican Border, MMS87-0025). This wealth of can at least be partially attributed to the discovery, delineation, and development of proven nd gas targets, the extensive coastal population concentration, and the large number of ersities in the area. A relative paucity of geologic research has been conducted in the study from Morro Bay, California, to Cape Flattery, Washington. This relative scarcity of data can aps be attributed to the lack of inherent characteristics previously listed for southern fornia.

While researching this project, particularly in the data-gathering phase, a concerted t was made to identify, contact, and obtain pertinent published and unpublished data. Data-ering efforts included computerized literature searches, published bibliography reviews, library archive searches, and contact with leading researchers either by phone or in person.

The results of the exhaustive data search efforts revealed that while there is a erately large body of geologic literature about the continental shelf, relatively little data exist ifically concerning the nature and distribution of late Pleistocene and Holocene continental sediments for the study area. Although the study area lacks the comprehensive raw data of hern California, several outstanding detailed studies have been completed in smaller, isolated ions of the Morro Bay to Cape Flattery continental margin. However, even with these studies, eader should not expect detailed interpretation of the late Pleistocene and Holocene sediment ibution, thickness, and nature for the entire study area.

1.2 Study Area

The study area (Figure II-1) is located between Point Buchon, California (35°15'N), and Cape Flattery, Washington (48°30'N), covering over 2,200 kilometers (km) of straightline distance. The study area includes the coastal zone up to at least 1.6 km inland from mean high tide level, and offshore to slightly beyond the continental shelf/slope break (which generally occurs between 125 to 175 meters (m) or at least 150 m water depth. The latter depth was chosen because it is slightly deeper than the probable maximum lowstand of sea level occurring during the late Pleistocene Wisconsin glaciation, and allows excessive coverage for detecting submerged landforms, near which prehistoric sites may be located.

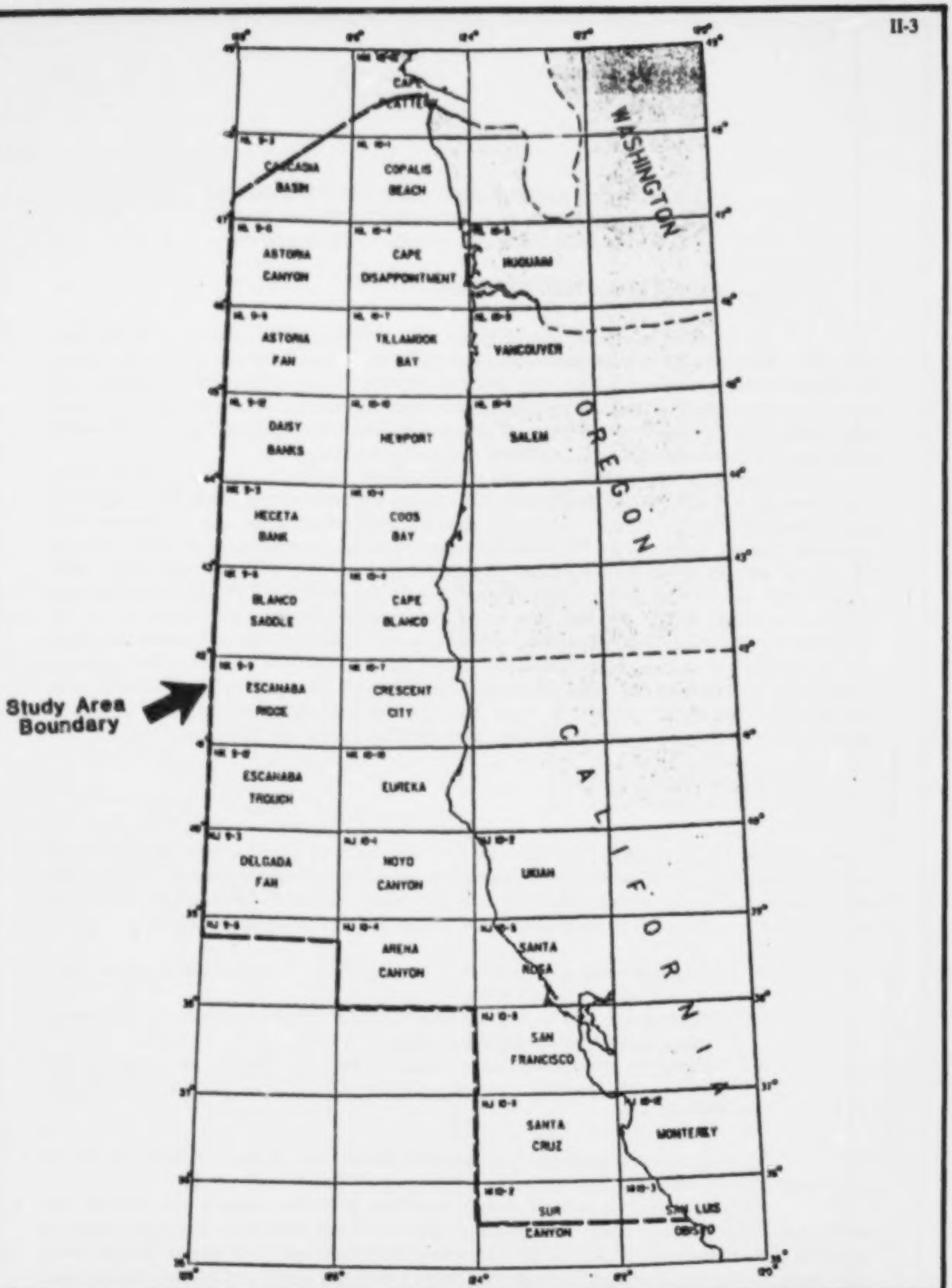


Figure II-1. Study Area for the California, Oregon and Washington Archaeological Study.

2.0 REVIEW OF LATE PLEISTOCENE AND HOLOCENE GEOLOGIC HISTORY, MODERN CONTINENTAL SHELF, CLIMATOLOGY, AND SEA LEVEL FLUCTUATIONS

2.1 Late Pleistocene and Holocene History

As expected in a study area as large as Cape Flattery, Washington, to Morro Bay, California, the coastal margin/continental shelf geologic history is complex and subject to a variety of diverse tectonic, sedimentologic, and physical regimes. This chapter is concerned with presenting an overview of the late Pleistocene and Holocene geologic history of the entire study area. Variations of this generalized overview will be addressed in succeeding sections of this report which detail individual physical environments composing the study area.

Although independent researchers have placed the Pleistocene/Holocene boundary at different dates, the Holocene Epoch of the Quaternary Period is currently defined as beginning at the conclusion of the Pleistocene Epoch, approximately 10,000 years ago. Holocene time continues through the present. The maximum late Wisconsin lowstand of sea level occurred between 20,000 and 17,000 Before Present (B.P.) (Kuhm et al., 1968; Milliman and Emery, 1968; Spigai, 1970; and Mullins et al., 1985) (Figure II-2). The 10,000 B.P. Pleistocene/Holocene boundary occurred during the post-Wisconsin Transgression, commonly referred to as the Holocene Transgression. For the purposes of the study, while the Pleistocene/Holocene boundary will be defined as occurring approximately 10,000 B.P., the primary scope of the geologic investigation will include the late-Pleistocene beginning with the onset of the post-Wisconsin Transgression, 20,000 to 17,000 B.P. Pleistocene time would then span from 1.6 million to 10,000 B.P. The Quaternary Period includes both the Pleistocene and Holocene epochs.

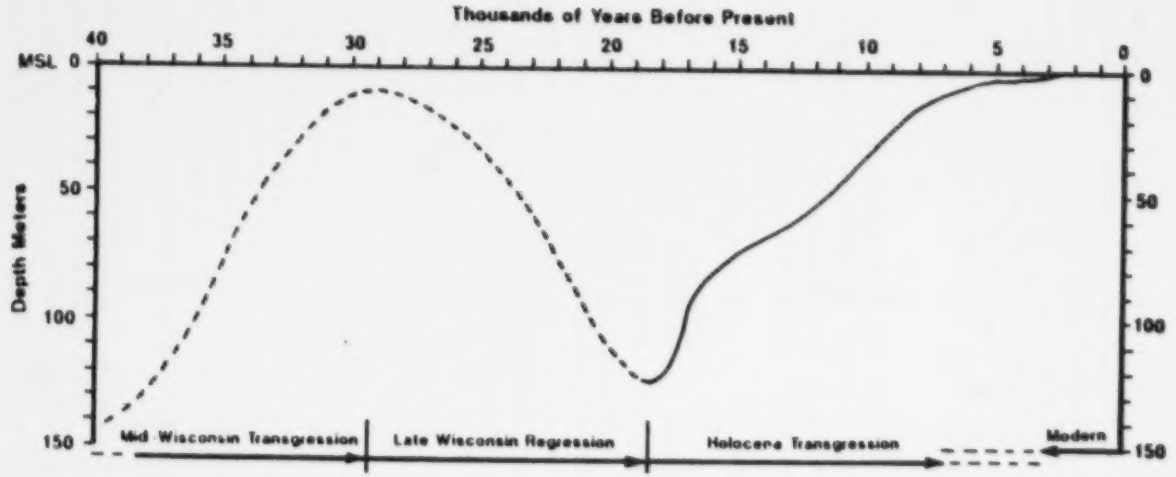
2.1.1 Tectonic History

Modern plate tectonic theory contends that the Earth's surface is composed of a number of large, distinct, rigid, lithospheric plates. Currently there appear to be seven large plates with dimensions of several thousand kilometers, and more than 20 smaller plates. These plates may be composed of thin oceanic crust (25 to 50 km thick), thicker continental crust (50 to 100 km thick), or a combination of both types. The boundaries separating plates include:

- divergent boundaries or spreading centers: zones of plate creation where plates move away from one another,
- convergent boundaries or consumption zones: zones of plate destruction where plates collide (e.g., subduction zones), and
- transform boundaries: zones where plates slip sideways past one another without the generation or consumption of crustal material (Gray and Kulm, 1985).

The plate boundaries are not discrete planes, but rather are broad zones of episodically active tectonic adjustments up to 500 km wide (Howell et al., 1980).

According to plate tectonic theory, upwelling of basaltic magma derived from the upper mantle has erupted along deep fractures that now form mid-ocean spreading ridges at divergent plate boundaries (Figure II-3). The newly formed oceanic crust moves laterally away from the spreading ridges as rigid plates at rates varying from less than 1 centimeter (cm) per year



Dotted curve estimated from minimal data. Solid curve shows approximate mean of compiled data.

II-5

Figure II-2. Late Quaternary Fluctuations of Sea Level (modified from Curray, 1965).

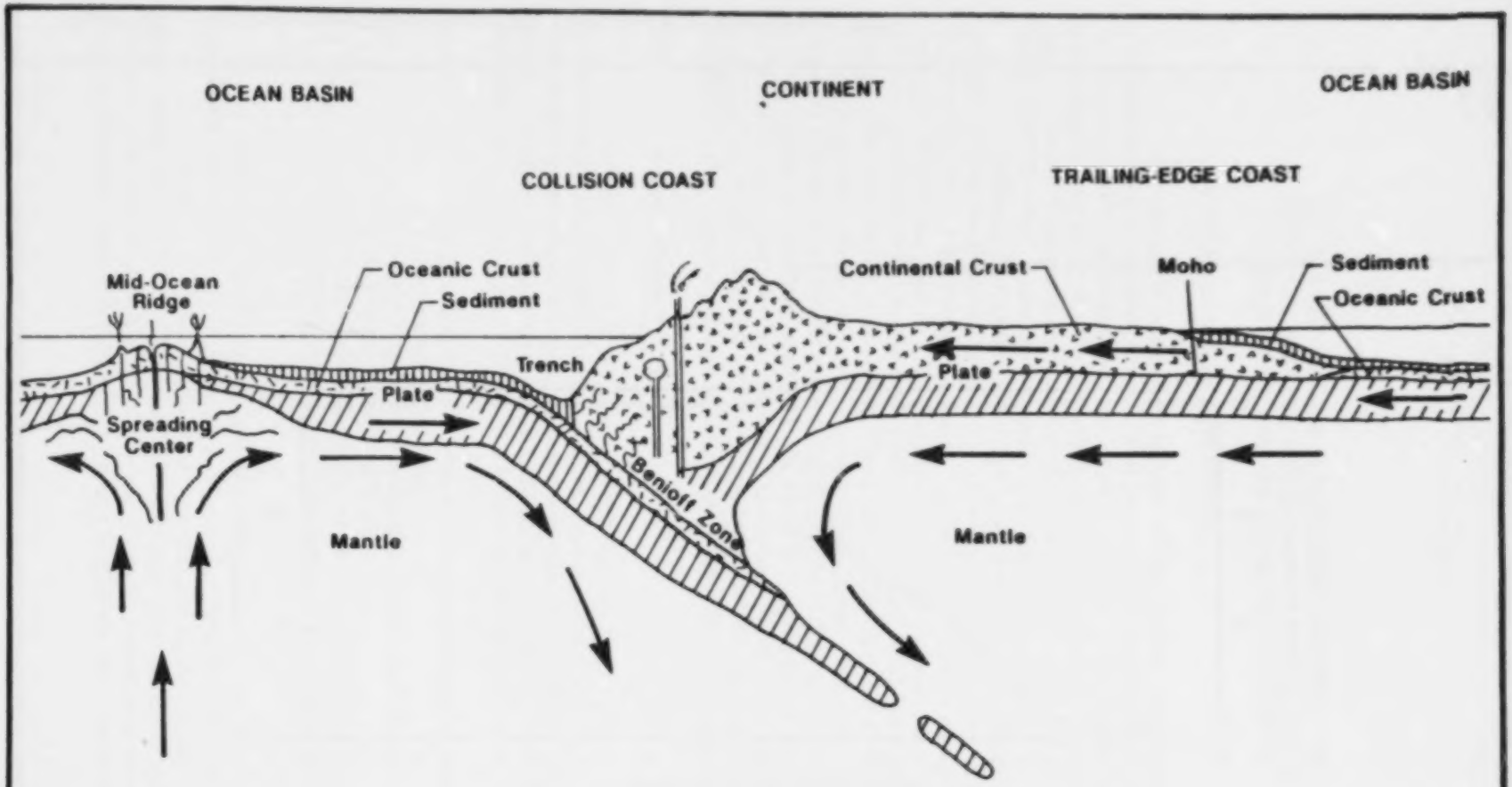


Figure II-3. Schematic Illustration of Plate Tectonics and Formation of Collision and Trailing-Edge Coasts (after Benioff, 1955 and Inman and Nordstrom, 1971).

oceanic plates continue to spread until they reach a convergent boundary, typically forming an oceanic trench. Since oceanic material is more dense than continental material, the denser oceanic plate is forced to plunge beneath the continental plate forming a subduction zone. The landward dipping-plane of earthquake hypocenters which marks the decending slab of lithosphere is known as the Benioff Zone.

In the western portion of North America, three major tectonic plates are recognized: the Pacific, Juan de Fuca, and North American plates. The tectonic control of the study area north of the Mendocino fracture zone (40°30'N) appears to be dominated by the underthrusting of the Juan de Fuca plate beneath the North American plate (Figure II-4). The portion of the study area south of the Mendocino fracture zone is dominated by transform boundaries separating the Pacific and the North American plates (including the San Andreas fault system).

Drake (1982) summarizes the Cenozoic tectonic history for much of the northern portion of the study area as follows:

- The early Eocene Farallon oceanic plate was separated from the Pacific plate by the ancestral East Pacific rise located in the mid-Pacific Ocean.
- A convergent margin was marked by a subduction trench separating the North American plate from the Farallon plate. The trench consumed the Farallon plate.
- Eventually the collision of the East Pacific spreading ridge and the subducting trench in mid-Tertiary time resulted in the creation of the San Andreas fault system. South of the Mendocino fracture zone, this right lateral transform fault system replaced the preceding subduction regime.
- Subsequent to the creation of the San Andreas fault system, only a remnant of the Farallon plate, the Juan de Fuca plate, existed north of the Mendocino fracture zone. Episodic spreading continued driving this much smaller plate in a different direction and rate relative to the ancestral Farallon plate.
- By Miocene time, motion was established in a northeast direction relative to the continent and oblique relative to the North American continental margin.
- Although smaller scaled underthrusting was sufficient to both uplift marine sediments on the outer continental margin and cause continental accretion, the driving force degraded.
- This smaller, less active subducting block began to break up into partially independent blocks. The two major blocks are the Gorda plate to the south and the Juan de Fuca plate to the north. These two plates are separated by the Blanco fracture zone.
- Most recently, while the Juan de Fuca plate may well continue to be underthrust beneath the North American plate, lateral and extensional adjustments are also occurring in the margin.

The continental margins of the study area north of the Mendocino fracture zone may be evolving from a compressional underthrusting to a transform strike-slip tectonic regime resulting from extensional forces and the coupling of the Juan de Fuca and North American plates.

The tectonic, depositional, and magmatic Cenozoic history of the northern half of the study area has been affected by episodic periods of underthrusting, transcurrent faulting and extension between the Pacific, Juan de Fuca (Farallon), and North American plates (Snavely and MacLeod, 1977). Periods of subduction were interrupted by major right-lateral, strike-slip faulting (Snavely et al., 1980).

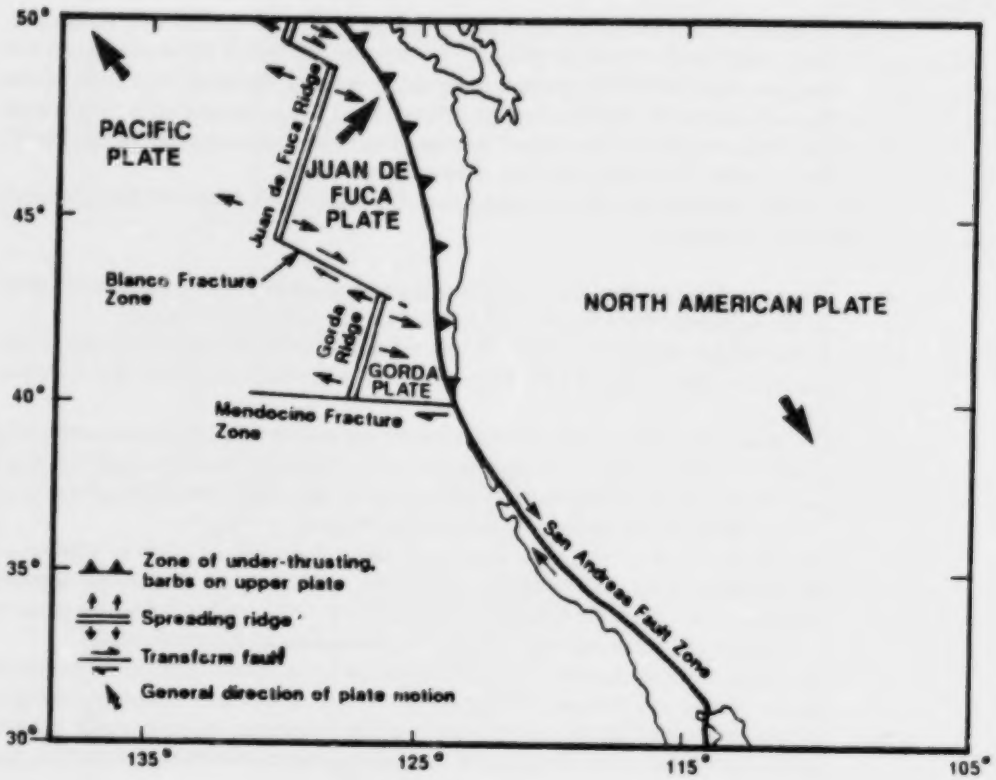


Figure II-4. Generalized Tectonic Map of U.S. West Coast (modified from Atwater, 1970).

Researchers disagree as to whether underthrusting is presently occurring beneath the northern California, Oregon, and Washington continental margins. Atwater (1970), Silver (1971, 1972), Drake (1982), and Gray and Kulm (1985) suggest that compressional oblique underthrusting is proceeding at a rate of 2 to 5 cm/year. Dehlinger et al., (1971) argue the area is presently undergoing extension and not subduction. Crosson (1972) and Leithold and Bourgeois (1989) suggest the area is experiencing transitional tectonism, where right-lateral strike-slip displacement is replacing convergence and subduction.

Two features typical of convergent plate margins, a well-developed Benioff zone and an oceanic trench, are absent along the Oregon-Washington coast. Atwater (1970) suggests that because of its relative youth and high temperature, the Juan de Fuca slab experiences few brittle failures and therefore generates few deep earthquakes. A high rate of sedimentation along the coast may actually lubricate the subducting block, allowing it to underthrust without great seismic disturbance (Drake, 1982). The absence of a trench could be explained by rapid sedimentation, a slow rate of convergence, or both.

However, very recent paleoseismic evidence from episodically subsided salt marshes, coastal tsunami deposits and continental slope turbidity deposits all indicate active coseismic subduction in the Cascadia margin (Atwater, 1987; Peterson and Darienzo, 1988; Darienzo and Peterson, 1990; and Adams, 1990). Of significance to this report is the strong correspondence between the coseismic subsidence and tsunami events (approximate 500-year recurrence intervals) and abandonment of coastal cultural sites. Sudden coseismic subsidence and/or deposition of thick tsunami sediment sheets may have protected cultural resources from the ensuing shoreface erosion of the Holocene Transgression.

Although there may be insufficient evidence for the absolute resolution of the problem of modern underthrusting in the northern half of the study area, the authors of this report believe that the Juan de Fuca plate is currently being obliquely subducted beneath the North American plate along what is referred to as the Cascadia Subduction Zone. This zone of underthrusting is nearly 800 km long extending from the Mendocino triple junction (point or small area where three tectonic plates meet) north to the unnamed triple junction at the south end of the Queen Charlotte fault. The interpreted trench axis lies as close as 60 km west of Cape Blanco, Oregon, and as far as 140 km west of Willapa Bay, Washington (Golder and Associates, 1986). The present rate of convergence is estimated to be between 20 and 40 millimeters per year (mm/year) (Adams, 1984; Davis et al., 1984).

As mentioned previously, the portion of the study area south of the Mendocino fracture zone is dominated by the San Andreas fault system. This transform fault system is over 1,600 km in length, strikes N35°W, and is characterized as exhibiting right-lateral strike-slip movement. Current displacement along the fault varies at different locations, but movement up to 3 cm/year and averaging 1.5 cm/year is common. Hill and Dibblee (1953) suggest displacement along the San Andreas fault of over 550 km since the Jurassic Period, and over 15 km since the Pleistocene Epoch.

2.1.2 Holocene Transgression

Changes in Pleistocene climate caused glacio-eustatic sea level fluctuations that strongly influenced coastal margins around the world. Periods of glaciation were associated with marine regressions and low stands, while interglacial stages were accompanied by advancing seas and high stands recorded by elevated, wave-cut terraces occurring along the coast. The post-glacial Quaternary Period in the study area is characterized by extensive deposition, changing regimes of sedimentation, and both sedimentary progradation and erosion (Spigai, 1970).

The great influx of sediments transported to the continental shelf during the Pleistocene Epoch originally covered much of the shelf, upper-slope and lower-slope of the study area. These Pleistocene sediments were deposited over a larger time period and at a greater rate than Holocene sediments; hence, the Pleistocene section is more widespread and thicker than the sediments deposited during the Holocene Epoch. Pleistocene sediments may reach thicknesses of 100-200 m or more on the outer shelf and continental slope (see Nittrouer (1978) for data concerning offshore Washington State, and Kulm and Fowler (1974) and Snavely et al. (1980) for data concerning offshore Oregon State).

Most researchers agree that sea level during the last stage of late Pleistocene Wisconsin-aged glaciation was approximately 120-130 m below present levels (Curray, 1965; Kulm et al., 1968; Emery, 1968; Spigai, 1970). This sea level position is important in providing seaward constraints to possible cultural sites on the OCS. Sea level evidence coincides with late Wisconsin continental glacial chronology, and suggests the general Holocene Transgression began about 18,000 B.P. (Curray, 1965) and was interrupted by several minor regressions. Relative to normal geologic standards, the Holocene Transgression can be considered an extremely rapid transgression representing a eustatic change in sea level of more than 100 m in less than 20,000 years.

The Holocene Transgression consists of two periods of different rates of sea level rise. A relatively rapid rise in sea level of 10 m/1,000 years occurred from 18,000 to 10,000-7,500 B.P., followed by a slower rate of advancement averaging 1.5 m/1,000 years. Eustatic sea level has remained relatively stable for the past 3,000 years (Figure II-2).

With the advent of glacial melting, enormous volumes of water were released into the oceans, and the shoreline retreated landward. As the sea transgressed, shoreface and nearshore sediments accumulated in front of the encroaching sea, depositing a blanket of transgressive sand. Nearshore and shoreline facies boundaries migrated in a shoreward direction resulting in overlapping transgressive facies. Successive nearshore deposits consequently onlap preexisting shoreline facies, which in turn subsequently bury the deeper water mud facies. Stillstands produced thicker accumulations on the ancient strandplains. Spigai (1970) estimates an average Holocene sedimentation rate over the entire continental margin of 50 cm/1,000 years.

Deposition of coarse clastic material on the shelf was significantly decreased between 10,000 and 7,500 B.P. as continental glaciation concluded, the rate of sea level rise slowed, and newly formed bays and estuaries trapped coarser sediments (Harlett, 1971). Consequently, shelf sedimentation changed and became characterized by the deposition of finer-grained material, and the physical and biological reworking of older sands previously deposited. Evidence suggests that much of the inner shelf sand is probably a relict transgressive sand sheet that was reworked during the Holocene Transgression. Most of the deposition of modern sand on the shelf has been restricted to the inner shelf while finer-grained sediments have been deposited on the middle and outer shelf (Oceanographic Institute of Washington, 1977). The uneven deposition of Holocene sediments has left extensive areas of Pleistocene sediments exposed or thinly mantled on the surface of the outer shelf and upper slope.

Evidence indicates that a large influx of subaerial, coarse-grained sediments were deposited on the continental margin during sea level lowstands of the late Pleistocene. During the Holocene Transgression, both reworking of previously deposited sand and the deposition of the greatly reduced volume and finer-grained influx of sediment resulted from rising sea level.

2.2 Modern Continental Shelf

Curray (1965) defines the continental shelf as a shallow submerged platform bordering the continents sloping gently seaward to an increase in slope referred to as the shelf break. This increase in slope separates the continental shelf from the more steeply dipping continental slope, and is found at a worldwide average depth of approximately 130 m (Figure II-5). The shelf break marks the topographic and structural edge of the continents, and is the boundary between the relatively shallow water covering the shelf and the greater depths of the remainder of the ocean proper. The width of the continental shelf ranges worldwide from zero to greater than 1,300 km, and averages nearly 73 km (Shepard, 1963).

Continental shelves have played an important role as sites of sediment accumulation throughout geologic time as witnessed by the extensive representation of shallow marine deposits in the geologic record. The continental shelves of the world represent a link between ocean basins and terrestrial environments. Because continental shelves are located at the boundary of the continental landmass and the oceans, shelf sedimentation is controlled by both onshore and offshore geologic and oceanic processes.

2.2.1 Geologic Control

Geologic control can be seen by the particular tectonic settings of the continental margins influencing sedimentation and the physiographic form of adjacent continental shelves. Continental margins located along collision coasts are relatively straight and mountainous, and are characterized by sea cliffs, raised terraces, and narrow continental shelves. They often contain zones of active seismicity and volcanism. Continental shelves located on the trailing edge of a continental plate are generally broad, with adjacent low-lying landmasses that have been eroded by mature drainage features (Inman and Nordstrom, 1971).

Modern continental shelves are the products of the Quaternary Period, and result from the repeated rise and fall of sea level. Eustatic sea level changes produced smooth, gently sloping platforms along the boundaries of continents (Nittrouer, 1978). Modern continental shelves formed as water released from the melting of glacial ice transgressed and further produced wave-cut, erosional surfaces mantled with reworked, regressive sediments and flooded continental margins.

Marine transgression can be considered a leveling process. Positive, pre-transgressive features such as hills are eroded by encroaching seas. Topographic lows act as local depo-centers receiving sediment removed from positive features. Marine transgression typically removes or redistributes 10 to 20 m of unconsolidated, previously deposited sediment (Kraft, 1971; Sheridan et al., 1974; Kumar and Sanders, 1975). Consequently few coastal landforms are preserved in the geologic record intact.

This leveling and reworking of near-surface sediments is of primary importance to the preservation of cultural resources. For instance, most prehistoric habitation sites located near paleo-shorelines would likely not be preserved, as the energetic environments of the encroaching Holocene Transgression inundated, reworked, winnowed and deposited sand at these sites. The key to cultural resource preservation appears to be location in a wave-energy shadow or in an area of rapid, yet calm, sedimentation below the level fo subsequent wave base erosion. Examples of wave-energy shadows include: back barrier facies or mainland shore facies located behind large, nearshore islands or fold belt ridges. Examples of facies that may experience rapid, yet calm, sedimentation include estuaries and portions of coastal floodplains. Belknap and Kraft (1981) suggest that, during periods of rapid sea level rise (such as the first half of the Holocene

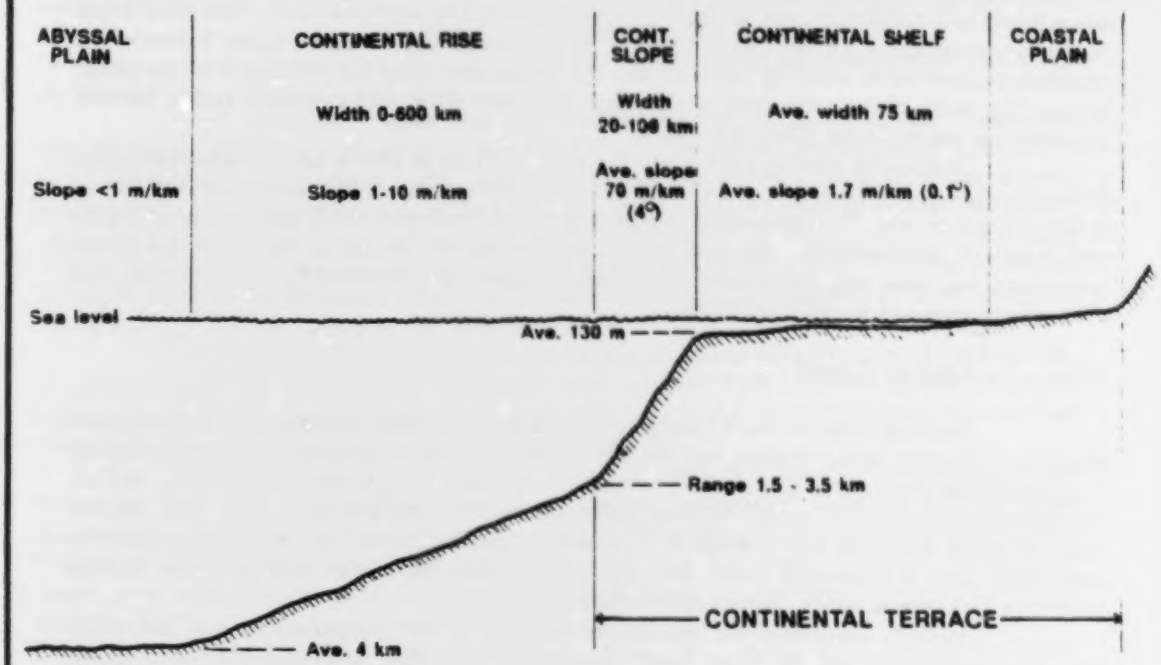


Figure II-5. Diagrammatic Profile of Continental Terrace and Continental Rise (after Curray, 1965).

Transgression), site preservation may be more likely to occur because of the shorter period during which sites would be exposed to shoreface erosion.

The changes in sea level have strongly controlled the configuration of shelf boundaries. Former river mouths are submerged, and some might have evolved into the heads of submarine canyons located on the shelf break. Some former river valleys have flooded and become estuaries.

Although the classificaiton of submarine canyons generally show little relationship to tectonic environments, they influence shelf circulation, and act as transportation conduits delivering sediments to the deeper ocean. Many low-gradient rivers are collecting coarse-grained sediment in modern estuaries because sediment supply has not been sufficient to maintain equilibrium with the rapidly rising sea level during the Holocene. However, rivers with high sediment discharge values, such as the Russian, Eel, Kalamath, Rogue, Columbia, and Quinalt, have filled their submerged river valleys, and are now contributing silt, sand, and gravel to the shelf (Karlin, 1980 and Nittrouer, 1978).

2.2.2 Oceanic Control

Oceanic processes clearly influence the dynamics of shelf sedimentation. Current regimes, wave activity, storms, density contrasts, tidal motions, and biological activities are known to influence sedimentological processes, which in turn will control the movement and accumulation of sediment derived from the adjacent terrestrial source. Physical processes generally control large-scale sediment dispersal on the shelf, while biological processes generally alter sediment after deposition.

2.2.3 Continental Shelf Sedimentation

Early continental shelf sedimentation theories were first formulated in the late 1800s, and predicted the shelf would approach an equilibrium state consisting of a concave-upward exponential profile in response to the expenditure of incoming wave energy. This early model predicted the development of an inner shelf abrasional platform and an outer-shelf constructional platform.

A corollary to this equilibrium profile theory predicted a texturally graded shelf. The coarsest-grained sediments would be found on the shoreface and the finest grained sediments on the outer-shelf. However, it was observed that this graded condition was not achieved in many shelves of the world (Borgeld, 1985).

Emery (1952) attempted to explain why the idealized texturally graded shelf is often not realized. In his study of surface sediments deposited on the California continental shelf, Emery differentiated detrital from relict sediments. He described the detrital sediments as those currently being supplied by rivers, currents, or wind to the areas of deposition. On a whole, the deposition of these detrital sediments tends toward the texturally graded conditions, and generally exhibits a systematic decrease in grain size in an offshore direction. Relict sediments are described as those deposited in an older and different physical regime (Borgeld, 1985). Relict sediments are those that are not modern, and are not in equilibrium with their present environment (Curray, 1965). They may be reworked and redistributed by shelfal currents and storms, but they are no longer in equilibrium with their original depositional environment. Relict sediments are recognized by their deviation from the texturally graded model, and are generally found to be coarser than the sediments presently being deposited.

Swift et al. (1971) refined the relict versus detrital or modern sediment differentiation by further describing palimpsest sediments as relict sediments that have been reworked by physical or biological process. These sediments may exhibit textural and petrological properties that are different from their precursor relict sediments. Such deposits have been described from the Oregon shelf by Kulm et al. (1975).

Curray (1960) considered the relation between shelf sedimentation and alternating marine transgressions and regressions. He recognized that coastal rivers supplied both sand and fine-grained material to the shelf. Sand tends to drop out of the fluvial system in the nearshore zone and is redistributed by wave and nearshore current action. Fine-grained sediments are carried in suspension and deposited independently of the coarser-grained fraction. Consequently, as marine conditions inundated coastal zones during periods of glacial melting, the nearshore sand body migrated landward forming a reworked blanket of sand across the ancient shelf. The suspended fine-grained sediments were deposited seaward of the shoreline. As marine transgression continued, these fine-grained sediments were deposited on the transgressive basal sand.

Modern researchers realized that one of the major factors influencing the occurrence and distribution of relict sediments on the modern continental shelves was the oscillatory nature of sea level during the Quaternary Period. This understanding resulted in the development of a general model describing the evolution of a continental shelf following a major rise in sea level. This model was specifically applied to the post-Wisconsin Holocene Transgression and is referred to as the Holocene Facies Model (Curray, 1960, 1964, 1965; Swift, 1970, 1974) (Figure II-6).

Borgeld (1985) summarizes the Holocene Facies Model as consisting of three phases described as:

- Authochthonous Phase: As marine conditions transgress, the shoreline migrates landward, inundating valleys along the coast. Shoreface material eroded during the transgression is transported offshore and redistributed. During the transgression, estuaries remain large and well-developed, effectively trapping fluvial sediments. The continental shelf is blanketed by relict sands left behind as the transgression proceeds.

- Allochthonous Phase: As estuaries fill with fluvial sediments, a portion of the riverine-suspended load begins to bypass the estuaries and begins to supply the shelf with fine-grained sediments. These fine-grained sediments tend to be deposited at a mid-shelf position, at depths below the level of storm waves. Given sufficient time, three major facies will develop on the continental shelf:

    1) nearshore sandy facies,
    2) middle shelf mud deposit, and
    3) outer shelf relict deposit which has been unaffected by modern sediment accumulation.

- Final Phase: Once sea level stabilizes, estuaries fill with sediment and fluvial systems return to a baselevel equilibrium. Riverine bedload and suspended load will then be directly supplied to the shelf where these sediments will be distributed according to oceanic and geologic processes. In essence, the texturally graded shelf model will be approached.

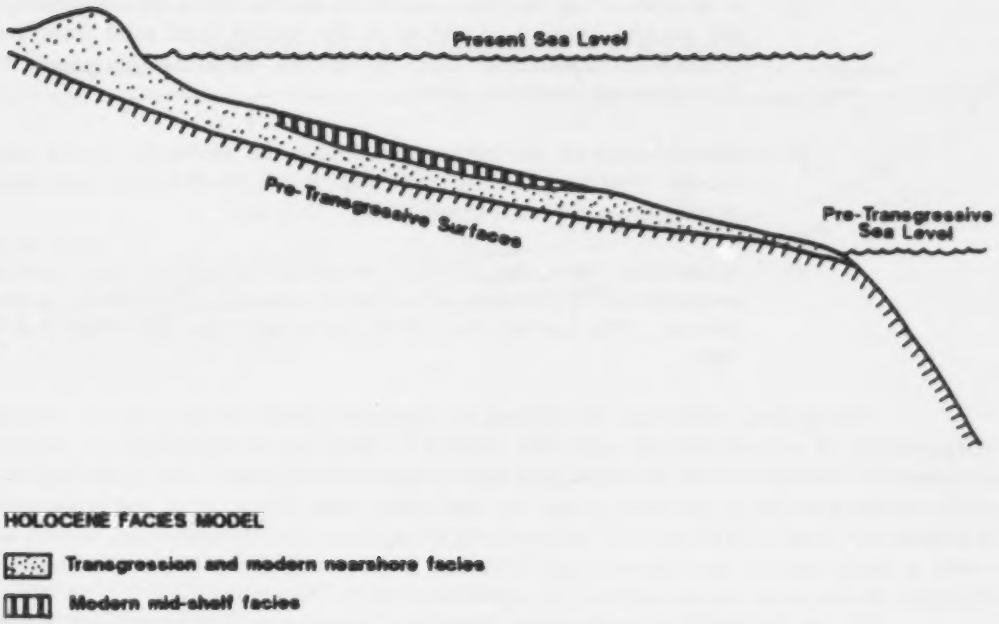


Figure II-6. Characteristic Shelf Stratigraphy Resulting from Sedimentation Following a Rise in Sea Level (from Curray, 1965).

Borgeld (1985) goes on in his dissertation to point out some of the more important consequences of subsequent model verification research concerning the Holocene Facies Model:

1) much of the relict sedimentation on modern continental shelves responds to physical conditions on the shelf (Stride, 1963; Lavelle et al., 1976; Vincent et al., 1981; Cook, 1982);

2) a variation of the vertical structure of allochthonous shelves results with the general offshore migration of the middle shelf mud from source (rivers) to depositional sinks (submarine canyons) (Nittrouer, 1978; Nittrouer and Sternberg, 1981);

3) establishment of the parameters driving the Holocene Facies Model, namely: riverine sediment input, shelf width, shelf history, and physical conditions on the shelf (Swift, 1970, 1974); and

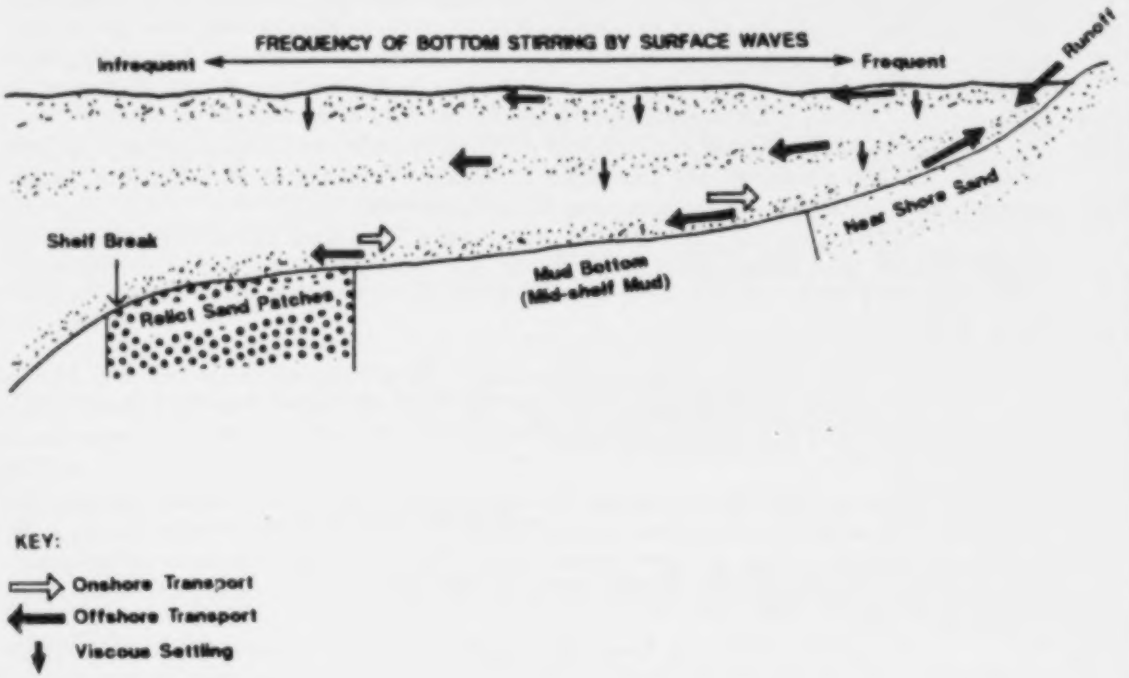
4) recognition that the oceanic processes offsetting shelf sediment accumulation (e.g., waves and currents) are most effective during storms (Murray, 1970; Lavelle et al., 1976; Cacchione et al., 1984; Field and Roy, 1985).

Fine-grained sediments transported in suspension from coastal areas are deposited independently of coarser-grained sediments trapped in estuaries or deposited in a nearshore environment. Several authors have indicated that fine-grained sediments travel suspended in the water column from the source area across the shelf (Pak, 1969; Costin, 1970; and Drake, 1971). McManus and Smyth (1970) provide evidence suggesting that current-transported bottom water is also a mechanism for carrying silt-sized sediment from coastal rivers across the shelf to be deposited on the outer continental shelf or continental slope (Figure II-7).

Due to the lack of comprehensive vibracoring or shallow drilling studies in this portion of the OCS, the models presented above have been neither tested nor verified. However, analyses of surface grab samples and shallow gravity cores (1-2 m of subsurface depth) suggest the overlapping of a transgressive mud facies overlying basal sands in Washington (Nittrouer, 1978) and Oregon (Kulm et al., 1975).

The Holocene Facies Model may be employed as a conceptual model for use in explaining both the Holocene Transgression and the process leading to the formation and condition of the modern continental shelf. The Holocene Facies Model can be used to work backwards to develop an understanding of paleo-continental margin/coastal margin conditions where cultural resources are most likely to have been both located and preserved. For example, using the Holocene Facies Model, archeologists may be able to estimate the thickness of the sediment overburden above older shoreface and lagoonal deposits. Additionally, predicted sedimentary facies distributions have implication for topographic mantling (Peterson, C. D., 1990, personal communication).

Although the Holocene Facies Model stresses physical (geologic and oceanographic) control rather than tectonic control of shelf sedimentation, the conceptual model will be utilized. Previously defined model terminology and concepts will be employed in the ensuing discussion of the geology of the study area.



KEY:

Onshore Transport

Offshore Transport

Viscous Settling

Turbid layers are indicated by wiggle patterns in the water column. Sources of suspended material are river runoff, biogeneous material in the surface waters, the surf zone, and the resuspended silts and clays deposited previously on the muddy areas of the continental shelf.

Figure II-7. Conceptual Model of Suspended Material Transport Across the Continental Shelf (modified from Harlett & Kulm, 1973).

2.2.4 *Sedimentary Facies of the Continental Shelf*

Sedimentary facies differentiation and distribution on the continental shelf of the study area result from a combination of Holocene sedimentation, distribution of relict sediments, authigenic processes, and oceanic physical processes.

The initial portion of the Holocene Transgression prior to 7,500 B.P. is characterized as a period of rapid sea level rise and, consequently, rapid marine transgression. During the early portion of the Holocene Transgression, sedimentary facies were transitory in nature. There was insufficient time for the deposition of a shelf facies to cover the basal transgressive sand. The modern outer continental shelf is thought to consist predominantly of relict reworked transgressive material. Spigai (1970) and Chambers (1968) did not detect any appreciable quantities of Holocene sand at the surface in shelf environments other than in the modern inner shelf.

Holocene muds transported 10,000 to 7,500 years ago by coastal-draining fluvial systems bypassed estuarine sediment traps and began to accumulate on the shelf. This fine-grained material was often mixed with the underlying basal transgressive sand.

Following the stabilization of sea level nearly 3,000 years ago at approximately its present position, three distinct facies developed on the continental shelf over much of the study area. These three facies were previously mentioned in the Allochthonous Phase of the Holocene Facies Model:

1) nearshore sandy facies,
2) mid-shelf mud facies, and
3) outer shelf relict facies.

The inner shelf facies represent the modern portion of the encroaching transgressive sand sheet. This sandy nearshore facies typically extends from the shoreline to water depths of 40 to 70 m and consists of fine- to coarse-grained sand. The inner shelf sand facies are generally 5 to 10 m thick except near river mouths where they can thicken considerably (U.S. Army Corp of Engineers (USCE), 1986).

The middle shelf mud facies is actually a deposit of mixed relict sand, basal transgressive sand and fine-grained Holocene sediments. Mixing is accomplished by wave action, currents, and biological agents. This mid-shelf mud deposit probably did not begin forming until the modern oceanic environment was established 7,000 to 3,000 years ago (Nittrouer, 1978). This facies generally occurs from depths of 60 to 70 m and continues to a depth of 120 to 130 m. The thickness of the mid-shelf mud facies varies from less than 10 to 20 m to greater than 50 m adjacent to large coastal rivers with high discharge and sediment supply.

The outer shelf relict facies typically occurs at depths greater than 120 to 130 m and extends to the shelf break or uppermost continental slope. This facies is characterized by irregular patches of modern fine-grained material and relict coarse-grained sandy sediments (USCE, 1986).

2.2.5 *Generalized Morphology Description of the Continental Shelf of the Study Area*

In general, the continental shelf of the west coast of the United States is much narrower than that of the east coast and Gulf coast. Shepard (1963) defines worldwide average shelf width to be 73 km. The width of the continental shelf in the study area ranges from over 50 km off the coast of Cape Flattery, Washington, to less than 1 km in parts of the central California coast. Average width of the continental shelf in the study area ranges in the order of 30 to 35 km.

Because of this narrow width, the mid-shelf mud facies covers the outer shelf and shelf break in many places (Curray, 1965).

Continental shelves on the tectonically active west coast of North America are also characterized as steep. Slopes of 0.5 to 1° are not uncommon (Bourgeois and Leithold, 1983). Sedimentation rates are often found to be much greater than rates for passive margin shelves (Howell and Von Huene, 1981).

The topography of much of the continental shelf in the study area is remarkably smooth especially compared to the adjacent onshore coastal topography. Exceptions to the smooth character are generally seen in the rocky portions of the shelf with little or no recent sediment cover. Submarine banks also interrupt the gentle topography of the continental shelf. Most submarine banks in the study area are at least partially fault-controlled structural highs occurring in the outer shelf region near the shelf break (Maloney, 1965). Basement highs such as the Farrallon Islands also interrupt the smooth shelf topography. Diapir and piercement structures commonly occur off the coast of the Olympic Peninsula, also disturbing the generally smooth surface of the continental shelf (Wagner et al., 1986).

Structural controls may have influenced cultural site occupation by either uplifting or downdropping coastal areas relative to sea level. Structural controls may have also influenced preservation of potential cultural sites by sudden subsidence and ensuing rapid burial below wave base destruction.

Submarine canyons incise both the continental shelf and slope, carrying sediments seaward, often depositing them in huge, prograding submarine fan complexes. These canyons often actively erode headward toward the shore through the continental shelf. Monterey Canyon in central California heads less than 1 km from the shore and is one of the world's largest submarine canyons.

2.3 Late Pleistocene/Holocene Climatology

Paleo-climatic data, largely based on pollen records, indicate that the climate in the study area during the late Pleistocene/Holocene was cooler and more humid than today (Heusser et al., 1980).

2.3.1 Pacific Northwest

Heusser et al. (1985) have established a temperature and precipitation profile for western Washington. The late Pleistocene/early Holocene was a time of stades and interstades associated with Wisconsin glaciation. This most recent glacial advance, locally referred to as Fraser glaciation, occurred between 25,000 and 10,000 B.P. Continental ice lobes advanced into the northern and central Puget Trough and to the present-day Strait of Juan de Fuca by 18,000 B.P. Both ice lobes retreated from a maximum position between 15,000 and 14,000 B.P., with an interruption in the recession occurring between 11,000 and 10,000 B.P. (Barnosky et al., 1987). Extensive alpine glaciation largely occurred between 22,000 and 19,000 B.P. in the Cascade Range and the Olympic Mountains. Some evidence of alpine glaciation is seen in the Coast Range of Oregon and the Klamath Mountains.

According to data obtained from pollen studies, a cold humid interval occurred during the late Pleistocene beginning approximately 28,000 B.P. Quantitative climatic reconstructions suggest that temperatures were lower than today's by 5° C, although precipitation was unchanged (Heusser et al., 1985). This cold interval continued until about 13,000 B.P. and terminated with a rapid increase in temperature. Increases in temperature continued until nearly 8,000 B.P. when

a temperature maximum was reached. A cooling period followed, and has only recently been replaced by a warming trend that continues to the present.

Precipitation was directly related to temperature during the late Pleistocene. As temperature decreased to its low level at 28,000 B.P., precipitation decreased as well. As the temperature began to rise at the end of the Pleistocene, precipitation increased. It then decreased abruptly at approximately the same time temperature increased to the Holocene maximum at approximately 8,000 B.P. Heusser et al. (1985) conclude that during the Pleistocene glacial periods, the climate of the Pacific Northwest was cold and relatively dry. During the interglacial periods, the climate was warmer with increased moisture. During the Holocene, periods of cool temperature were accompanied by greater precipitation, whereas periods of warmth were drier. This reversal suggests that the climate controls in effect during the last period of glaciation differ from those in effect today.

Pollen data collected from the Pacific Northwest indicate that the Wisconsin continental ice sheet had only a secondary effect on the coastal vegetation. In the past, as is true today, the Pacific Ocean had a moderating effect on the climate. A cold humid climate is implied from the vegetational record between 20,000 and 18,000 B.P. The paleo-ecologic record suggests that moisture was confined to the area west of the Olympic Mountains and Pacific storms did not penetrate far inland. As the climate began to warm, nearly 18,000 B.P., summer drought became evidenced by paleo-vegetation records. Early Holocene vegetation indicates increased summer drought until approximately 8,000 B.P. Contrary evidence, however, suggests that increased precipitation occurred at high elevations (Barnosky et al., 1987). During the late Holocene, increased precipitation and decreased summer drought characterized the climate of the Pacific Northwest. The climate by 5,000 B.P. is thought to have been similar to the modern climate.

2.3.2 California

The climate of coastal California appears to have been rather consistent throughout the Quaternary. The mild, wet winters and warm dry summers that define California's present coastal climatic regime were also part of the region's climate throughout the late Quaternary, as suggested by paleo-ecologic evidence. Because of this consistency, it is believed that the factors which presently control climatic conditions in coastal California were operative throughout the late Quaternary (Johnson, 1977).

Paleo-ecologic evidence including marine, geologic, pedologic, paleo-botanic, dendroclimatic and historic precipitation data has led Johnson (1977) to conclude that the modern Mediterranean climate of much of coastal California has persisted throughout much of the Quaternary. The climatic zone probably experienced a slight southward shift during the last glaciation which corresponded to a southward shift or weakening of the Pacific subtropical high. Slight variations in the Mediterranean-type climate and local changes in temperature and precipitation were likely to have occurred during glacial periods. Meteorological factors responsible for mid-latitude glaciers were probably also responsible for local precipitation increases and lower temperatures. A steepening of air temperature gradients in the north Pacific, resulting from the presence of an ice sheet 3 km thick stretching from the western Cordilleras to the Atlantic, would probably have been accompanied by a deepening of the Aleutian low circulation. As a result of such a deepening, there was probably a stronger winter precipitation regime that began earlier in the fall than at the present, and lasted later into the spring.

Steepened air temperature gradients in the north Pacific would also ultimately lead to an increase in upwelling and vertical mixing along the coast. Because of such an increase, cool upwelled water would cause a decrease in surface water temperatures, increase in fog, and cooler

temperatures along the coast. Such conditions would reduce summertime evapotranspiration and generally reduce annual temperature extremes. In addition, the slight shifting of the Pacific subtropical anticyclone may have led to cooler and perhaps more moist summers than occur presently.

Climatic warming began nearly 13,000 years ago and reached its mid-point by about 11,500 B.P. in the Coast Ranges of northern California (Adam, 1985). A westward and northward spread of hot dry climatic conditions followed. A period of warming and drought, termed the Xerothermic period, began about 8,000 B.P. and lasted until nearly 3,000 B.P., after which there was a return to cooler conditions. Although this interpretation is still being verified, if correct, it would correspond to a larger pattern of warmer and drier conditions documented in other areas during this interval.

2.4 Sea Level Fluctuations

The relative changes in position of worldwide sea level during the late Quaternary have been largely subject to eustatic control related to changes in glacial ice volumes (Birkeland, 1972). Variations of sea level have been further determined by both regional plate tectonism and local tectonic adjustments. Tectonism plays a more significant role in controlling sea level along active continental margins than along passive continental margins (Dickinson, 1974). Relative sea levels for late Quaternary time are best defined from radiocarbon dating of continental shelf sediments. A partial list of material used for recent dating includes: shallow water mollusks, woody plant remains, beach rock, and salt marsh peat that initially accumulated near sea level.

Dupre et al. (1980) report geologic evidence of a rising Holocene sea level in the Monterey Bay, California area including: onlapping marine sediments, thick fluvial aggradational sequences, and wave-cut platforms. Evidence of a falling sea level includes stream downcutting into coastal valleys and deposition of a regressive veneer of marine and terrestrial coastal terrace deposits.

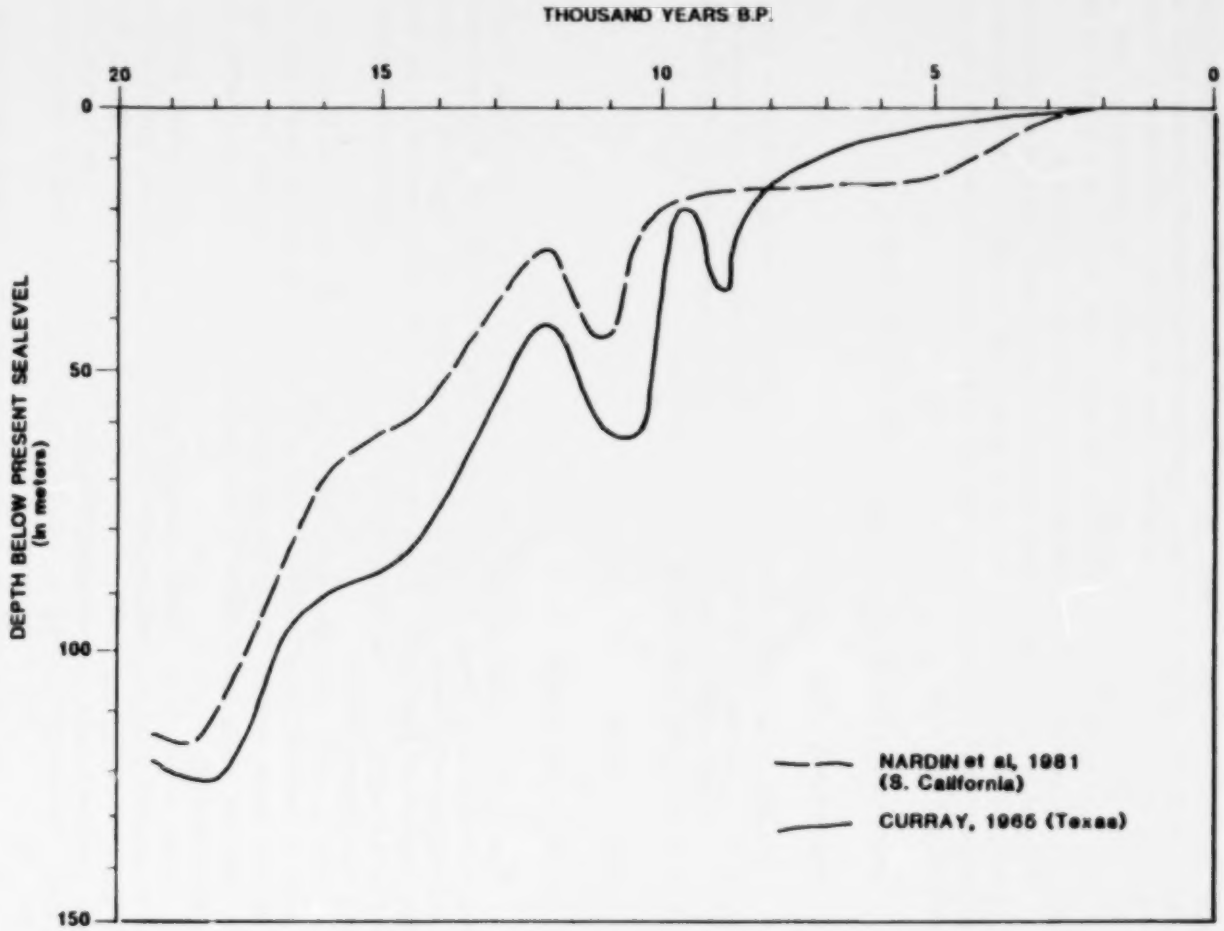
Late Quaternary sea level fluctuations along the broad continental shelves of both the Gulf coast and the east coast have been extensively studied. In contrast, relatively little research has been conducted concerning Quaternary sea level fluctuations in the study area. Much of the data used to interpret sea level fluctuations along the coast of the study area need to be extrapolated from studies conducted elsewhere. Unfortunately, because coastal areas around the world are subjected to different types and amounts of tectonic influence, sea level curves appear to be strictly valid in detail only for those areas in which the study was conducted (Nardin et al., 1981). Eustatic sea level fluctuations (worldwide changes of sea level that affect all the oceans) can be adjusted to individual localities if area-specific tectonic uplift or subsidence, isostatic rebound and sedimentation data can be applied, resulting in a relative sea level curve.

Although little evidence exists along the west coast, most researchers indicate a mid-Wisconsin interstadial highstand occurred between 35,000 and 22,000 B.P. (Curray, 1965; Milliman and Emery, 1968; Hoyt et al., 1968). After reaching this high stand, which approximates the current shoreline position, sea level dropped slowly at first and then more rapidly until about 19,000-18,000 B.P. The 19,000-18,000 B.P. sea level was established approximately 125 m below the present level. This level and date appear consistent with late-Wisconsin glacial chronology, temperatures indicated by pollen profiles, and isotopic and faunal measurements of deep-sea sediment (Curray, 1965; Emery and Garrison, 1967; Nardin et al., 1981; Mullins et al., 1985).

Shortly after reaching the late-Wisconsin sea level minimum approximately 19,000-18,000 B.P., the climate began to warm, glacial ice started to melt and retreat, and sea level began to rise. The Holocene Transgression (Flandrian Transgression) resulted from this rising sea level.

Most researchers portray the Holocene Transgression as a rapid, smooth, steady rise in sea level until between 10,000 and 7,500 B.P. (Milliman and Emery, 1968; Dillon and Oldale, 1978). However, detailed data from southern California indicate that during the first 8,000 years of the Holocene Transgression, sea level rapidly rose to approximately 30 m below present level, quickly fell to -45 m, and then rose again to -20 m by 10,000-9,000 B.P. (Nardin et al., 1981). This mid-Holocene fall of sea level from -30 m to -45 m is not reflected in Curray's (1965) generalized late Quaternary fluctuations of sea level curve (Figure II-2). This reversal is, however, mirrored in Curray's (1965) data from the Texas Gulf coast (see Figure II-8). Evidence of a now-submerged wave-cut terrace at 50-60 m depth off the California coast also supports the notion of the mid-Holocene reversal (Mullins et al., 1985). The succeeding Holocene Transgression from approximately between 10,000 and 7,500 B.P. is characterized by a slow rise in sea level without discernible interruption until reaching its present position nearly 3,500 B.P. (Nardin et al., 1981).

One of the sea level curves plotted on Figure II-8 portrays a generalized sea level curve for the past 20,000 years along the southern California continental margin. The authors believe that this generalized curve represents the best, most current sea level curve for the entire study area. Since individual portions of the study area have been affected by different types and varying rates of tectonic adjustment and isostatic response, this generalized sea level curve will be modified for specific portions of the study area. These specific modifications will be addressed in the Sea Level Fluctuation section of each subregional Physical Environment chapter.



II-23

Figure II-8. Sea Level Curves for the Past 20,000 Years Along the Southern California and Texas Continental Margin (modified from Mullins et al. 1985).

3.0 PHYSICAL ENVIRONMENTS

For ease of discussion, the study area has been separated into four subregions based on similarities of the geologic history and currently active geologic processes. These subregions extend from Cape Hattery to Heceta Head; Heceta Head to Cape Mendocino; Cape Mendocino to Morro Bay; and the San Francisco Bay area. Discussion of each subregion includes a general characterization of the area followed by descriptions of the coastal physiography, tectonic history and setting, shelf physiography, geology, oceanographic setting, late Pleistocene/Holocene stratigraphy, sea level fluctuations, and Holocene thickness maps, as well as a section on the specific features judged to have the greatest potential for prehistoric occupation.

The authors of Volume III have divided the overall study area into six geographic subareas. The limits of the subareas are defined by geopolitical boundaries. The boundaries of the four subregions of Volume II are based on geologic parameters, and thus do not coincide with the six subareas of Volume III.

3.1 Cape Flattery, Washington, to Heceta Head, Oregon (44°N)

3.1.1 Delineation of Area

The width of the continental shelf from Cape Flattery, Washington, south to Heceta Head, Oregon (44°N), averages 40 km (Figure II-9). South of Heceta Head, the continental shelf narrows, and the average width ranges less than 25 km. This change in shelf width defines the southern limit of the northernmost subregion of the study area.

3.1.2 Regional Setting

3.1.2.1 Coastal Physiography

The coastal physiography of the northern portion of the study area (Cape Flattery, Washington, to Heceta Head, Oregon) is characterized as relatively straight, affording few barriers to large-scale offshore circulation. Coastal geomorphology varies from rugged, rocky headlands to extensive beaches and dune fields. Erosion rates along unprotected coastal areas can range from less than 0.5 m/year for rocky coastlines up to 13.5 m/year for unconsolidated Quaternary sands and gravels (Byrne, 1963).

Starting to the north, the western side of the Olympic Peninsula from Cape Flattery south to the Grays Harbor/Copalis Beach (47°N) area consists of a broad uplifted coastal plain with locally developed coastal terraces. Landforms comprising this section of coastline include: rugged headlands, cliffs, sea stacks, pocket beaches, some small islands, small bays and estuaries, and elevated marine terraces.

South of the Grays Harbor area to the Columbia River, the coastal margin is composed of low-relief beaches, dunes, and spits nourished by accretion of sand derived from the Columbia River, rare rocky headlands, and elevated estuarine terrace deposits. The southern Washington coastline is more subject to a rapid erosional change than the rocky, more resistant northern coast. Three major estuaries are located along this portion of the coast: Grays Harbor, Willapa Bay, and the Columbia River estuary.

South of the Columbia River in northwestern and central Oregon, the coastline is dominated by the uplifted terraces cut into rocks of the Coast Range. The coastline from the Columbia River to Heceta Head is composed of rocky headlands, numerous sea stacks, several

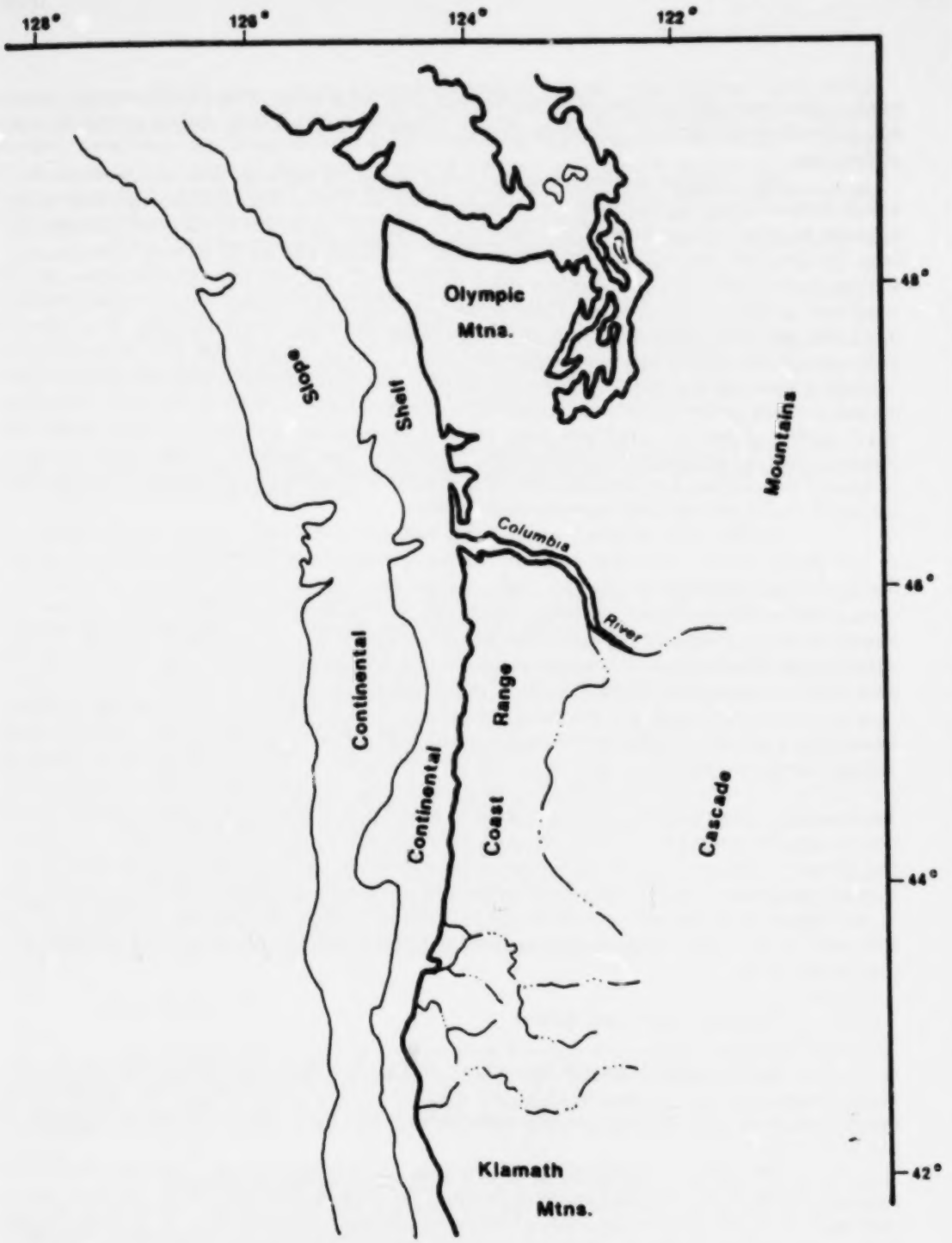


Figure II-9. Location Map of the Cape Flattery, Washington, to Heceta Head, Oregon (44 degrees), Portion of the Study Area (from Kulm and Fowler, 1974).

small isolated bays and estuaries, sand beaches and dune fields accreted to a narrow coastal plain, and elevated marine terraces. One large estuary, Tillamook Bay, is also located along this portion of the coast.

The estuaries located along the coastal margin of the study area are drowned river valleys formed during the Holocene Transgression. Schubel (1971) describes drowned river valley estuaries as ephemeral features. Their existence is primarily controlled by basin morphology, sea level changes, and long-term sedimentation rates. Estuaries located in tectonic active-margin settings, such as that of the northern portion of the study area, are generally characterized by conditions leading to rapid infilling. These conditions include: narrow river valleys, coastal tectonic uplift, and abundant supplies of river sediment (Boggs and Jones, 1976; Peterson et al., 1984). Kulm and Byrne (1966) and Scheidegger and Phipps (1976) characterize such depositionally "mature" estuaries as possessing shallow water depth, coarse-grained bottom sediment, and efficient bypassing of fine-grained sediments transported by rivers to the open coast environment. Peterson et al. (1984), however, point out that modern depositional patterns are not necessarily representative of deposition throughout the Holocene. For example, in one small, fluvially dominated Oregon bay, the oldest deposits (10,000-8,000 B.P.) are composed largely of fine-grained sediments (Peterson, personal communication, 1990).

Marine terraces were formed during high sea level stands, and have been preserved by continental uplift. Elevated wave-cut marine terraces were probably formed during the Pleistocene and late Pliocene (Runge, 1965), and are prominent along the northern Washington, Oregon and northern California coasts. There are no Holocene-age terraces located along the Washington and Oregon coastline (Golder and Associates, 1986). The youngest uplifted marine terrace of the Washington/Oregon coast is located in southern Oregon near Cape Blanco, and has been dated as developing 42,000 B.P. (Golder and Associates, 1986).

The Columbia River is the dominant source of sediment deposited on the Southern Washington shelf. Subordinant sediment sources include: the Strait of Juan de Fuca, smaller rivers in Washington and northern Oregon, and local shoreline erosion. Transport of sediment generally is to the north, and is in evidence by the formation of sand spits across the mouths of some rivers and estuaries. Estuaries trap most coarse-grained material from coastal rivers and streams, though fine-grained sediments bypass these traps and are introduced to the shelf environment. Strickland and Chasan (1989) estimate the Columbia River discharges 10,000 times more sediment to the Washington continental shelf than all other sources combined. However, Columbia River sands do not extend north beyond Point Grenville (47°18'N) (Venkatarathanam and McManus, 1973). Nittrouer (1978) estimates the Columbia River supplies 10,000,000 metric tons of sediment per year to the shelf.

3.1.2.2 Tectonic History and Setting

A discussion of the regional tectonic setting of Cape Flattery, Washington, to Heceta Head, Oregon, was included as part of Section 2.3.1, which summarized the tectonic history of the entire study area. The following section expands upon that overview for the northern region of the study area.

The geologic history of the Washington and northern Oregon coast and continental shelf has largely been controlled by the collision of the Juan de Fuca and North American plates during Tertiary and Quaternary time. Tectonically induced compression is in evidence in the folded and faulted marine sedimentary rocks of western Washington (Rau, 1973). Tertiary sedimentary and volcanic rocks of this region were deposited in two separate environments which have shifted with time. A deep marginal basin existed in early to middle Eocene time in most of

western Oregon, Washington, and the adjacent continental margin. This marginal basin evolved into a shelf environment during late Eocene to Pliocene times as the marginal basin migrated seaward in response to a change in the position of the plate boundaries (Snavely et al., 1977). The present continental margin of the northern part of the study area is interpreted to be part of the leading edge of the upper plate (North American plate) in a convergent plate boundary setting. The continental margin lies above a low-angle, eastward-dipping overthrust zone.

Rau (1973) interprets the extensively deformed sedimentary and volcanic rocks of the Olympic Peninsula and coastal area as remnants of the Juan de Fuca plate which were not subducted below the North American plate approximately 50 million years ago. These rocks were "skimmed" off the top of the subducting plate, foreshortened by compressional forces and successive underthrusting, and accreted onto the leading edge of the North American plate. Wave-driven erosion has subsequently leveled the western portion of the accreted terrain, leaving the continental shelf and low-relief western portion of the Olympic Peninsula and the southern Washington coast.

The Siletz River and Tillamook Highland volcanics of the Oregon coast are interpreted similarly to the Olympic Peninsula, as oceanic crust and oceanic island accreted onto the continental margin (Baldwin, 1976).

3.1.2.3 Shelf Physiography

The interstadial rising sea levels and high wave energies of the Pleistocene resulted in a number of transgressions creating an erosional shelf platform. Areas of tectonic emergence are characterized by relatively rapid shore cliff retreat resulting in the entrenchment of small coastal streams incising uplifted coastal terraces. Stable or subsiding areas are characterized by erosion at the shoreface, resulting in the reworking of penecontemporaneous eolian, estuarine, and fluvial deposits. During marine transgression, coastal valleys which formed during the lowstand of sea level were filled with fluvial, aggradational deposits. The geometry of the deposits result largely from the relative rise and rate of rise of sea level, coastal stream gradients, sediment supply, and the shelf/shoreline configuration during the transgression (Dupre, 1975).

Generally, in areas of tectonic emergence, the interglacial strandline is characterized by wave-cut cliffs in uplifted terrace deposits or bedrock. In areas of tectonic subsidence or stability, the strandline is characterized by low-relief coastal plain features such as dune fields. Shoreline erosion generally continues in areas of high wave energies and low fluvial inputs. Coastal progradation may be associated with large fluvial systems and high sediment influx. Large floodplains and alluvial fans may develop in areas of subsidence (Dupre, 1975).

Washington Shelf

The Washington continental shelf parallels the rugged coastline, trends approximately north-south, and extends over 200 km northward from the Columbia River mouth. McManus (1972) locates the shelf break at a depth ranging between 140 and 185 m. The width of the continental shelf ranges from 15 km off the Columbia River to greater than 50 km off Cape Flattery.

The Washington continental shelf is broken by six subsea canyons. These canyons were cut by large glacially fed rivers that dissected soft marine sediments at the shelf break during Pleistocene lowstands of sea level (Snavely et al., 1977). From north to south these canyons are: Juan de Fuca, Quinault, Grays, Guide, Willapa, and Astoria (see paleo-landform maps). As the canyons grew in a headward direction, they locally narrowed the width of the shelf.

The general bathymetry of the southern Washington continental shelf is characterized as a featureless seaward dipping surface with an offshore gradient which is constant or varies smoothly. This topography results from voluminous Columbia River sediments which have been transported northward and have masked basal irregularities (Nittrouer and Sternberg, 1981).

South of Point Grenville, the inner shelf and middle shelf form a smooth surface, while the outer portion exhibits a rougher, more relict topography.

North of Point Grenville, the nearshore shelfal topography is more irregular as witnessed by the numerous seastacks and small islands. Destruction Island, located 5.5 km offshore north of Kalaloch, is the largest island off the Washington coast, and the first major island north of the Farallon Islands near San Francisco. The middle shelf and outer shelf are relatively smooth, but show some evidence of irregularities including diapiric and piercement structures (Wagner et al., 1986). A broad topographic valley trends across the shelf off Cape Flattery and joins the Strait of Juan de Fuca to the north. The valley system is interpreted as a fluvial valley cut during lowstands of sea level. Venkatarathnan and McManus (1973) describe a steep nearshore surface that drops down to a wide terrace at a depth of 30 to 40 m near Cape Flattery.

Northern Oregon Shelf

The Oregon continental shelf north of Heceta Head appears to be similar to the southern extension of the Washington shelf described previously. The shelf parallels the north-south- trending coastline, and averages about 40 km wide, attaining a maximum width of nearly 70 km to the south near Heceta Bank. The average depth to the shelf break is similar to that of the Washington continental margin.

The only large submarine canyon cut into the northern Oregon shelf is the Astoria Canyon. The head of the Astoria Canyon is 16 km west of the mouth of the Columbia River (Snavely et al., 1977). A number of smaller submarine canyons and valleys cross the continental margin off northern and central Oregon (Figure II-10).

The continental shelf extends seaward from the straight, but rugged, coastline as a gently sloping plain. Similar to Washington, the smooth bathymetry of the Oregon shelf reflects younger sediment masking basal irregularities.

Several prominent shallow submarine banks rise from the Oregon continental margin. In the northern portion of the study area these include: Heceta/Perpetua, Stonewall, and Nehalem banks (Figure II-11). The banks are generally outlined by 50- to 60-m contours and exhibit relief of 75 m (Snavely et al., 1977). Kulm and Fowler (1974) describe Tertiary rocks cropping out on the banks, and Quaternary sediments onlapping their flanks. Interpretation of seismic profiles suggests that most of the banks are complex structural highs (Snavely et al., 1977).

3.1.2.4 Geology

The continental and coastal margins of Oregon and Washington, the Oregon and Washington Coast Ranges, and the Olympic Peninsula represent a portion of a regional-scaled, north-south-trending, Tertiary-aged depositional trough where as much as 8,000 m of Tertiary sediments have accumulated. The width of the trough extended from the Cascade Mountains to near the base of the present continental slope, while the length extended from Vancouver Island south to the Klamath Mountains (Snavely et al., 1977; Oceanographic Institute of Washington, 1977).

As mentioned in Section 3.1.2.2, Tertiary sedimentary and volcanic rocks of the Washington and northern Oregon coast and continental shelf were deposited in two separate

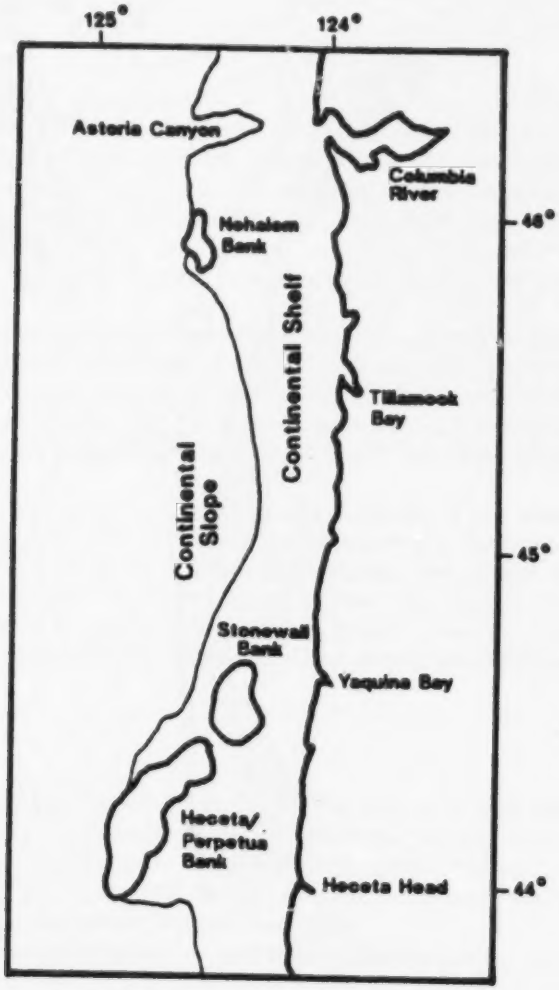


Figure II-10. Location of Submarine Banks off Northern and Central Oregon Coast.

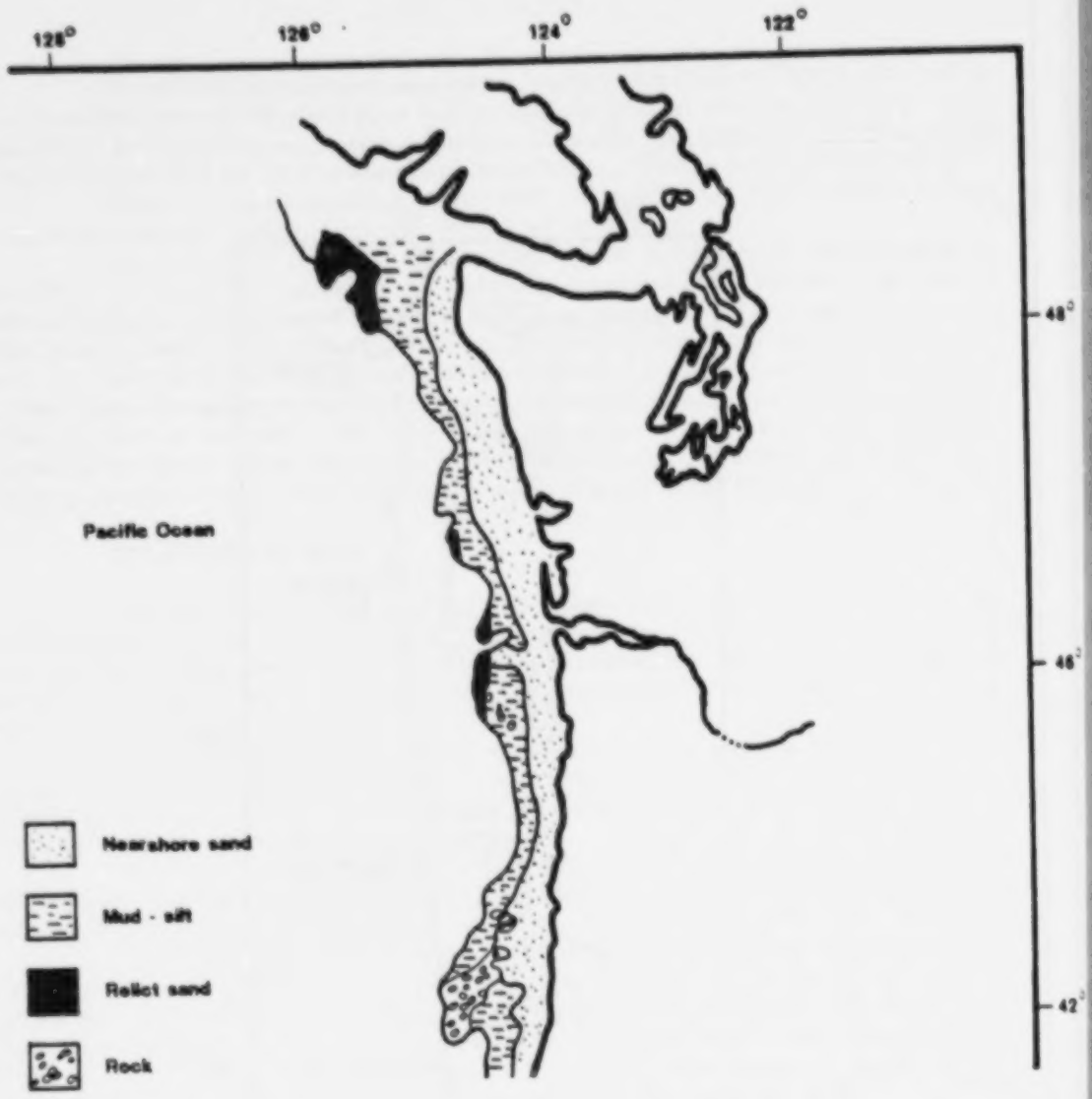


Figure II-11. Washington/Northern Oregon Surficial Sediment Data (modified from Gross et al., 1967 and Kulm et al., 1975).

environments that have shifted with time. The former deep marginal basin was floored with early Eocene oceanic material. A mid-upper Eocene regional unconformity separates these older rocks from an upper Eocene to Pliocene shelf sequence. Quaternary sand, silt, and interbedded gravel mantle the Tertiary rocks throughout the northern portion of the study area. These poorly consolidated rocks and unconsolidated sediments achieve a thickness of up to 500 m along parts of the inner continental shelf.

Continental

Tabor and Cady (1978) describe two Tertiary bedrock terraces occurring within the Olympic Peninsula. The peripheral Crescent Formation is composed of Tertiary marine sedimentary and volcanic rocks, and form a crescent wrapping around the core rocks, open to the west. The core rock assemblage is known as the Soleduck Formation, and is composed of sandstone, siltstones, marine basalts, and cherts that have been deformed and slightly metamorphosed. Extensive glacial deposits cover much of the coastal areas and Olympic Mountains.

The coastal range of southwestern Washington is referred to as the Willapa Hills. Volcanic flows of Miocene-aged Columbia River Basalt crop out near the center of the Willapa Hills. These volcanics were in turn partially covered by younger, mainly clastic debris shed off the ancestral Willapa Hills and Olympic Mountains, and deposited in a nearshore/coastal margin environment. Piedmont alluvial fans of glacio-fluvial origin were deposited during Pleistocene time in the Willapa Hills.

The Oregon Coast Range extends from the Columbia River south to the Klamath Mountains. The central core of the Oregon Coast Range, occurring in the northern portion of the study area, is composed of thick submarine volcanic flows, breccia, and tufaceous sedimentary rock of the Eocene Siletz River volcanic. The west and north sides of the Oregon Coast Range contain younger clastic rocks deposited in nearshore/coastal margin environments. Streams of the Coast Range have been incising their valleys as the range rose slowly during Plio-Pleistocene time (Baldwin, 1976).

Oceanic

Because of the complexity of the region and the paucity of offshore stratigraphic data for the entire study area, it is generally assumed that offshore stratigraphy, structure, and lithology are continuations of adjacent onshore units. The oldest rocks in the Washington and Oregon shelf are early Eocene volcanics that form the effective basement, or subsurface boundary. The Tertiary basin sequence is thought to overlie that volcanic basement.

The bedrock underlying poorly consolidated Quaternary rocks and sediments of the Washington continental shelf and coastal margin are composed mainly of lower Eocene(?) to middle Miocene turbidity and melange sequences (Rau, 1973, 1977). These rocks underlie the shelf and coastal margin, and lap onto the Tertiary rocks of the westernmost Olympic Peninsula and southwestern Washington Willapa Hills. Snavely et al. (1977) indicate that as much as 300 m of these Tertiary sediments may be present on the shelf. A thick Quaternary sequence overlies the Tertiary section.

Folds and faults mapped on the Washington continental shelf are recorded by numerous unconformities and anticlinal structures. Folds and faults generally trend north-northwest (Snavely et al., 1977). Numerous diapiric structures occur across the shelf starting near Willapa Bay and increasing in number to the north.

The Washington continental shelf has experienced marine deposition during much of Tertiary time lasting until Pliocene/early Pleistocene time, when deformation and faulting commenced. Deformation, faulting, and diapric piercement continued and erosion and truncation of structures was followed by modern sediment deposition and reworking on the shelf.

Snavely et al. (1977) described marine sedimentary rocks ranging in age from Eocene to Pliocene underlying much of the Oregon shelf. Nearly 2,000 m of early Eocene sandstone and siltstone have been penetrated by offshore drilling. Miocene and Pliocene rocks occur on the submarine banks off the Oregon coast. Similar to the Washington shelf, a thick Quaternary section of poorly consolidated rock and unconsolidated sediment overlies the Tertiary section.

Most structural features trend north or northwest on the shelf. Marked unconformities separate Pliocene and Pleistocene strata from older underlying Tertiary rocks (Snavely et al., 1977).

3.1.2.5 Oceanographic Setting

Several authors report that circulation on the Washington and Oregon continental shelf is controlled by large-scaled regional weather systems occurring in the Gulf of Alaska (Hopkins, 1971; Smith and Hopkins, 1972). Kachel (1980) summarized the work of a number of authors and stated that the West Wind Drift of the north Pacific Ocean bifurcates between 500 and 250 km off the Washington coast into the northward-flowing Alaska current and the southward-flowing California current.

During the winter, in response to the development of a mean atmospheric low-pressure cell in the Gulf of Alaska, southerly winds create Ekman transport in the surface layers toward the coast, resulting in coastal downwelling. The coastal downwelling destroys stratification, allowing northerly baratropic currents (Davidson current) to dominate (Nittrouer, 1978).

During the spring the regional winds shift, causing offshore Ekman transport in the surface layers and the formation of coastal upwelling (Hickey, 1979). Southerly baratropic currents result, and if a sharp pycnocline is present, a northerly bottom current may develop (Nittrouer, 1978). The transition from the winter Davidson current to the spring upwelling regime occurs rapidly.

The late summer and early fall current regime is described as a transitional phase from the spring upwelling conditions to the winter downwelling conditions, when wind strength and consistency is not great enough to maintain either condition. A weak southerly surface flow exists during this time, and deep flow is to the north (Borgeld, 1985). Stratification is generally weak during this period.

The currents near the mouth of the Columbia River are complicated by tidal currents and estuarine circulation (Barnes et al., 1972; Sternberg et al., 1978). Reid et al. (1958) noted that upwelling was more pronounced south of capes and other seaward extensions of land.

3.1.3 Representative Late Pleistocene/Holocene Stratigraphy

The Pleistocene/Holocene geologic history and stratigraphy of the northern portion of the study area has been complicated by eustatic sea level changes, northern glacio-isostatic rebound and tectonism. This section will concentrate on the representative late Pleistocene and Holocene stratigraphy of the continental shelf and adjacent coastal margin for the northern portion of the study area.

3.1.3.1 Late Pleistocene/Holocene Differentiation

A scarcity of data differentiating Holocene sediments from Pleistocene or older sediments or rocks has been encountered while searching both published and unpublished literature sources concerning the study area. This scarcity of data can perhaps be attributed to the lack of proven economic oil- and gas-related targets occurring in near-surface sediments.

Subsea seismic investigations of near-surface sedimentary units typically employ high-resolution, shallow-penetration, seismic reflection profiling. Researchers throughout the entire study area have utilized multi-vintage geophysical surveys to fill in gaps in their existing database. Unfortunately, many of these profiles were designed for low-resolution, deeper penetration. Even using the best data, the differentiation between Holocene sediments and older geologic material is difficult and often impossible.

Most researchers place the Holocene/Late Pleistocene boundary at the first surface of deformation. This surface of deformation is defined as a plane truncating sedimentary features or separating overlying undeformed deposits from underlying deformed strata. The Holocene section is thought to be represented by an acoustically transparent unit. This unit is assumed to be unconsolidated because of its acoustically transparent nature, its relative thinness, lack of well-developed internal reflectors, and stratigraphic position (Field et al., 1980).

The unconformity separating the Holocene/Late Pleistocene is interpreted as a result of erosion during a late-Wisconsin lowstand of sea level. It is apparent, however, that if no deformation or truncation occurs below the late-Wisconsin erosional unconformity, and if the two lithologies above and below the unconformity are similar in character and density, differentiation will be problematic. In this case, the first surface of deformation would represent an older lowstand, and the resulting pick would occur in Pleistocene or possibly older strata.

3.1.3.2 Pleistocene Stratigraphy

The Pleistocene Epoch began 1.5 million years ago with the advent of continental glaciation. At their maximum southern advance, continental glaciers covered the northern third of Washington, and alpine glaciers covered much of the Olympic Mountains. At least four glacial cycles are recognized in the Pacific Northwest during Pleistocene time. During periods of glacial advance, summer temperatures were estimated to be 10°F colder than today (Rau, 1973). During interglacial periods of melting, the climate was similar to that of today.

As the ice sheets advanced they deposited thick, widespread accumulations of unconsolidated, poorly sorted sand, gravel and silt. These deposits were spread by fluvial systems fed by glacial meltwater that thinned toward the coast. Pleistocene glacial outwash covers much of the Tertiary bedrock on the Washington coast. During Pleistocene lower sea level stands, westerly flowing fluvial systems incised the exposed continental margin, depositing sediments in floodplain, deltaic, and shallow marine environments. Sediments were then reworked into beach and shallow marine deposits which were reworked again during the subsequent transgression.

Episodic glacial advances and retreats were accompanied by dramatic changes in sea level. Wave-cut platforms developed during ancient still stands. These subsequently raised Pleistocene marine terraces occur discontinuously along much of the coast of the study area at elevations up to 400 m (Golder and Associates, 1986).

Work by Milliman and Emery (1968) and Bloom et al. (1974) indicates the last Pleistocene interglacial highstand of sea level occurred near its present level between 30,000 to 35,000 B.P. From that late Pleistocene highstand, sea level dropped slowly, exposing beach and nearshore shelf deposits until approximately 21,000 years ago. Between 21,000 and 18,000-19,000

B.P., sea level dropped more rapidly, reaching a maximum late-Wisconsin lowstand of about 120 to 130 m (Bloom et al., 1974; Curray, 1961).

3.1.3.3 Holocene Stratigraphy

Approximately 18,000 years ago, the climate began to warm, the ice sheets began to melt, and sea level started to rise once again. The shallow stratigraphy of the Washington and Oregon shelf represents deposits resulting from this eustatic sea level rise, the Holocene Transgression.

As the Holocene Transgression commenced, the characteristic shoreface/inner shelf environment migrated shoreward depositing a basal transgressive sand layer on the present-day continental shelf (Nittrouer, 1978). Sand accumulations in this blanket deposit thickened in response to periods of still stand. Rising seas flooded the exposed late-Pleistocene regressive surface, and wave energy reworked much of the unconsolidated sediment. Continued transgression resulted in the destruction and reworking of the Pleistocene coastal features such as shorelines, bays, and estuaries. About 5,000 to 7,000 years ago, modern fluvial muds and silts, which by-passed estuarine traps, began to accumulate below wave base and in less turbulent areas of the continental shelf (Kulm et al., 1975). These sediments were both mixed with underlying basal transgressive sand through biological and physical processes, and deposited above the transgressive sand. A mid-shelf silt deposit resulted, separating modern nearshore sand from outer shelf relict sand.

As sea level reached its approximate present position 3,000 to 7,500 years ago, the continental shelf of the northern portion of the study area began to closely resemble that which is predicted in the Holocene Facies Model. According to the Holocene Facies Model (described in Section 2.4.1), after a transgressing shoreline stabilizes, three major facies should develop:

1) nearshore sandy facies,
2) mid-shelf silt facies, and
3) outer shelf relict sand deposit.

The surficial sediment distribution of the Washington and northern Oregon continental shelf can be characterized by these three facies, the boundaries of which nearly parallel the shore (Figure II-11).

The nearshore sandy facies represents the modern exposed position of the Holocene Transgression. This sandy facies parallels the shoreline and may extend to depths of over 100 m along the Oregon coast (Runge, 1965). Gross et al. (1967) report that the nearshore sandy facies extends to an average depth of 90 m, but near the Columbia River the seaward boundary occurs as shallow as 60 m.

The transgressive basal sand unit seaward of the nearshore environment is overlain by the mid-shelf silt deposit (Figure II-12). Nittrouer (1978) describes the mid-shelf silt deposit to be closely dependent on stabilized shelf hydrodynamics, and reports that the deposit did not begin forming until the time sea level reached its present position approximately 3,000 to 7,500 years ago. For the majority of the northern portion of the study area, sediments composing the mid-shelf silt deposit were derived from the Columbia River. The mid-shelf silt deposit of the Washington continental shelf extends north-northwest away from the Columbia River, and thins away from its axis from a maximum thickness of 20 m (Nittrouer, 1978).

Outer continental shelf and slope Tertiary and Pleistocene rocks are overlain by the basal transgressive sand which can now be considered a relict sand, or, if reworked, a palimpsest sand. These relict sand accumulations generally occur at depths below 120 m (Nittrouer, 1978).

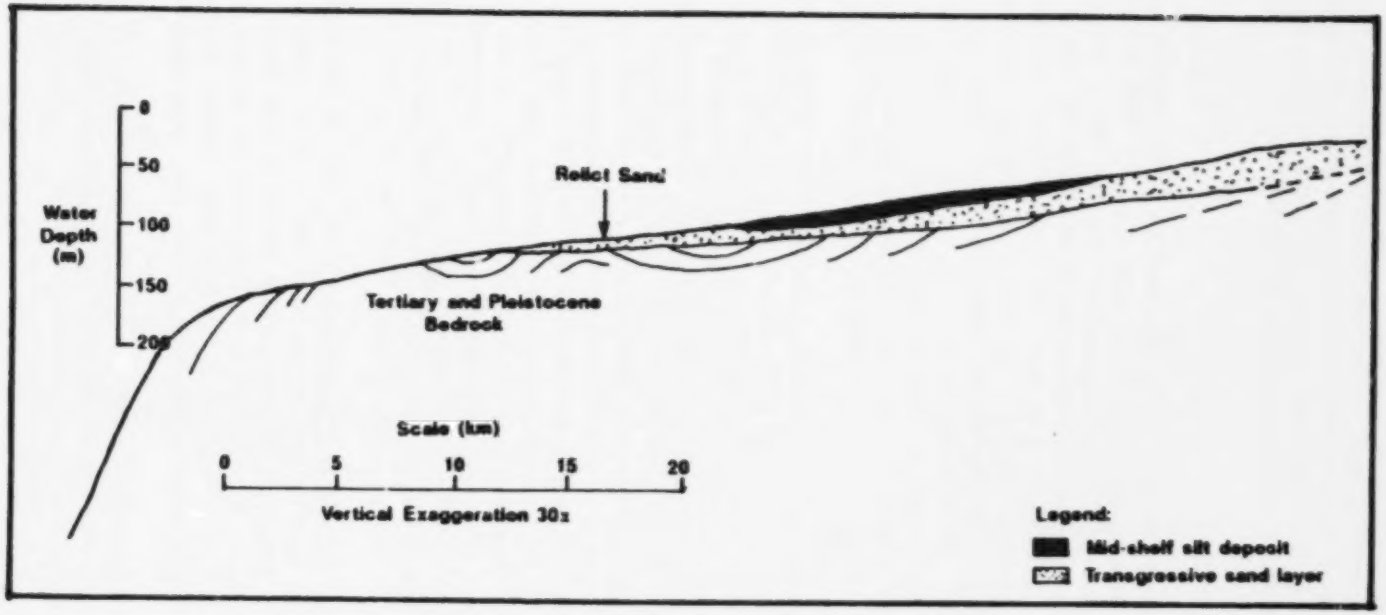


Figure II-12. Representative Holocene Stratigraphy Across Washington Continental Margin (modified from Nittrouer, 1978).

Relict sand has been reported on both the outer Oregon and Washington shelf, but its aerial extent is limited, and occurrence is local. Tertiary and Pleistocene bedrock form an irregular surface on the outer shelf where thin accumulations of relict sand occur. As the Holocene Facies Model describes, the outer shelf relict sand possibly represents sediment previously deposited in a shoreface and nearshore environment during the initial phase of the Holocene Transgression.

3.1.4 Sea Level Fluctuations

Continental shelves distributed around the world are products of the Quaternary. The Quaternary shoreline has retreated and advanced across the shelf of the study area at least four times since the onset of Pleistocene glaciation (Bowman, 1972). Maximum marine regression associated with each glacial period located the shoreline near the edge of the present continental shelf. The shelf break appears to be genetically related to these lowstand depths. As the climate began to warm, glacial ice began to melt and erosive marine transgression proceeded. The transgressions at least partially leveled shelfal topography which may have developed during regressive phases. Shoreline positions during maximum transgressive interglacial periods approximated today's present position and were recorded by wave-cut marine terraces.

These changes in sea level occurred rapidly relative to geological time, and resulted in a broad, gently sloping wave-cut platform mantled with a thin veneer of recent unconsolidated sediment, the continental shelf.

Beginning nearly 18,000 B.P. as the most recent glacial period (Wisconsin) began to culminate, enormous volumes of water released from melting glaciers caused sea level to rise approximately 125 m. During the beginning of the Holocene Transgression, marine inundation proceeded as rapidly as >10 m/1,000 years, until between 10,000 to 7,500 B.P. when the rate of sea level rise slowed to an average of 1.5 m/1,000 years (Chambers, 1968). Sea level has remained relatively static for the past 3,000 years, with the possible exception of 1-2 m fluctuations resulting from coseismic upper plate flexures (Darienzo and Peterson, 1990).

Although no complete Holocene sea level curves specific to the Northwest region were identified during the background literature and data search, several researchers have supplied data concerning sea level position during the late Pleistocene and Holocene time. Peterson et al. (1984) reported sediments at the Pleistocene/Holocene boundary (approximately 10,000 B.P.) in Alsea Bay, Oregon, to be 50 m below present sea level. Unpublished data from Grays Harbor, Washington, suggest 11,000-year-old sediment to be 60 m below present sea level (Peterson, C. D., 1990, personal communication). Glenn (1978) reports 9,000-year-old sediment found 30 m below present sea level in Tillamook Bay, Oregon. These basal sediments give some indication of past sea level.

Three sea level curves are plotted in Figure II-13. The Milliman and Emery (1968) curve is a relative curve for the Atlantic coast and its use is considered inappropriate due to extensive isostatic influences affecting the Atlantic shelf. The Nardin et al. (1981) data from southern California are also displayed as a relative curve and is again possibly inappropriate for the rest of coastal California and the Pacific Northwest. Melanie Stright of the MMS suggested employing the Curray (1965) eustatic curve as the base from which relative sea level can be calculated.

Several late Pleistocene and Holocene sea level positions have been plotted on the paleo-landform maps attached to this report. The approximate position of the individual Holocene sea levels were calculated using the following equation:

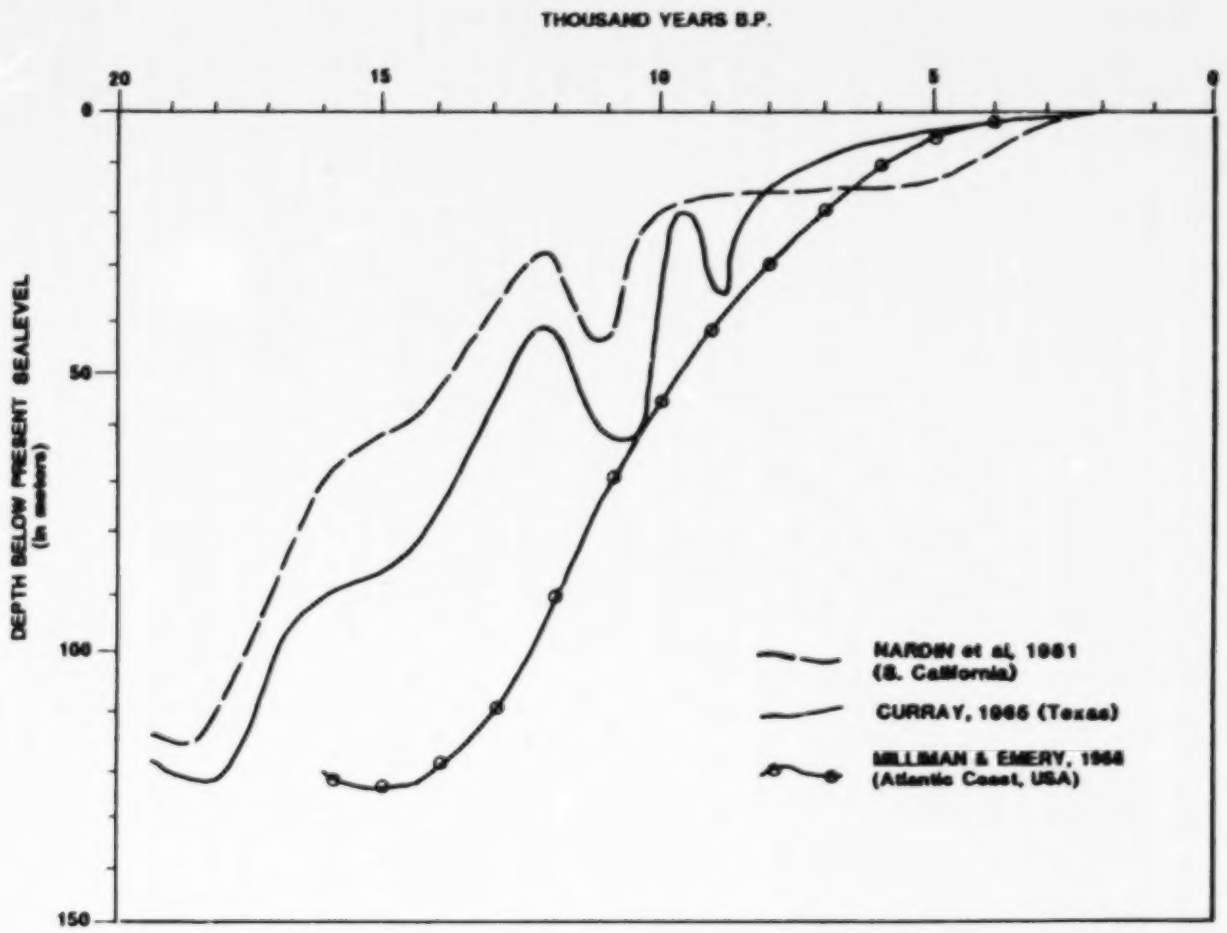


Figure II-13. Representative Sea Level Curves for the Pacific Northwest (modified from Mullins et al., 1985 and Milliman and Emery, 1968).

$H = h \pm h_o$, where

H = elevation of Holocene sea level relative to modern position,
h = sea level position at subject time extracted from Curray (1965), and
h_o = amount of tectonic adjustment or isostatic compensation.

In determining Holocene sea level position, a third variable may be considered. The amount of sedimentation (i.e., sediment thickness) will effectively shift the lateral position of sea level, but Holocene sedimentation is considered to be generally very thin throughout the entire study area, so this variable was not considered in our estimates.

In the northern portion of the study area, Holocene sea level positions were plotted for 18,000, 15,000, 10,000, and 7,500 B.P. (see Volume IV). No younger sea level positions were plotted because of the proximity of the 7,500 B.P. position to the current-day shoreline.

As previously stated, sea level rose at an average annual rate of greater than 10 m/1,000 years until between 10,000 and 7,500 B.P. As the Wisconsin-aged continental ice sheets disappeared, the rate of sea level rise slowed to about 1.5 m/1,000 years until the shoreline stabilized near its present position nearly 3,000 years ago. During the first half of the Holocene Transgression when seas rose rapidly, strandlines were relatively transitory, and thus long-duration coastal site occupation was generally precluded. However, due to the transitory nature of the coast, occupation sites were exposed to the erosive shoreface for a shorter period of time and therefore may have had a greater chance of preservation. The converse is true of the second half of the Holocene Transgression when seas rose slowly. While longer duration coastal site occupation was now possible, the length of time the submerged site was exposed to the erosive shoreface also increased.

Although the rate of post-glacial sea level rise temporarily overwhelms tectonic processes, the amount of tectonic uplift was considered in all sea level calculations. The entire coast of the Pacific Northwest has been subjected to tectonic uplift throughout the Quaternary (Golder and Associates, 1986). Several authors have reported varying rates of tectonic uplift throughout the northern portion of the study area (Adams, 1984; Peterson et al., 1984; Golder and Associates, 1986). The average rate of tectonic uplift considered in the sea level equation for the northern portion of the study area was 0.4 m/1,000 years (Golder and Associates, 1986). An example of how tectonic uplift adjusted sea level position is provided below:

$H_{18,000\ B.P.} = h \pm h_o$, where

$H_{18,000\ B.P.}$ = present elevation of 18,000 B.P. shoreline,
h = sea level position extracted from Curray's (1965) generalized sea level curve at 18,000 B.P.,
h_o(0.4 m/1,000 years) (18,000 years) = 7.2 m, and
$H_{18,000\ B.P.}$ = -125 m + 7.2 m = -117.8 m.

Biederman (1967) reports, from an integration of data in the Pacific Northwest, that deglaciation in western Washington was completed prior to 13,000 B.P., and isostatic adjustment due to glacial unloading was completed prior to 7,000 B.P. Again, since the rapid rate of sea level rise during the early Holocene overwhelms the amount of isostatic rebound, this component was not considered in our calculations.

3.1.5 Holocene Sediment Isopach Maps

Several factors controlling the thickness of unconsolidated, late Pleistocene/Holocene sediments accumulated on the continental shelf of the west coast include:

1) late Pleistocene shelf topography resulting from Pleistocene transgressive and regressive cycles,
2) fluvial, coastal, and continental shelf sediment sources and quanitity,
3) continental shelf marine currents controlling sediment distribution patterns, and
4) sediment bypassing of the continental shelf into shelf break canyons (Wagner et al., 1972).

The Holocene Thickness Maps for the northern portion of the study area are actually surficial geology maps of the continental shelf. With the exception of limited coverage in Grays Harbor and at the mouth of the Columbia River, no Holocene sediment isopach data could be found in either published sources or unpublished archived repositories. In southern California, numerous oil companies have funded research providing a large body of shallow drilling hazard reports (geohazard reports) which describe the thickness and nature of unconsolidated late Pleistocene/Holocene sediments. Unfortunately, without the proven economic targets, the northern portion of the study area lacks the detailed specific research to adequately define regional trends of Holocene sediment thickness.

In spite of the volume of continental shelf seismic data coverage available for the northern portion of the study area, researchers have not been primarily concerned with interpreting the thickness of Holocene sediment from seismic records. This is partially due to limitations of the source (sound) and recording instruments, and partially due to the problematic nature of the late Pleistocene/Holocene contact. Most researchers throughout the study lump Holocene and late Pleistocene unconsolidated sediments into a single acoustically transparent package, and do not differentiate between the Holocene and Pleistocene (Wagner et al., 1972; Field et al., 1980; Clarke et al., 1985).

The surficial geology exhibited in the accompanying map series depicts the geology of the continental shelf and upper slope as if the seawater and overlying sediment layer were removed. Wagner et al. (1986) report that the surficial geology of the Washington continental margin was largely drawn from interpretations of seismic reflection profiles which were tied to wireline sonic log data from offshore exploratory wells. Some near-surface water bottom sediment samples and onshore geologic data were employed mainly to substantiate correlations.

Although no Holocene sediment isopach maps for the Washington continental shelf were identified, Holocene sediment cover is described as thin, and broken in a number of areas by outcrops of older rocks and diapir/piercement structures. Nittrouer (1978) describes Holocene sediments resting directly upon truncated Tertiary bedrock indicating that pre-existing Pleistocene sediments were eroded and removed. Holocene sediments north of Quinault Canyon are thought to range in the order of 10 to 20 m thick (Field, M.E., 1989, personal communication).

South of Quinault Canyon, sediments from the Columbia River are transported northward and deposited on the continental shelf and slope. McManus (1972) reports that most Columbia River-derived sand accumulates nearshore while most silt accumulates on the mid-shelf region. Holocene sediment thickness south of Quinault Canyon appears thicker than that further to the north off the Olympic Peninsula, but is still found to be generally less than 20-30 m thick.

South of the Columbia River, the surficial geology of the Oregon continental shelf is simply distinguished by either undifferentiated Quaternary through late Miocene sediments and

poorly indurated rock versus Tertiary and older sedimentary rock. Although the dominant direction of transport of Columbia River sediment is to the north or downslope into Astoria Canyon, the northern Oregon continental shelf receives some sediment, especially proximal to the mouth of the river. Kulm and Peterson (in press) report that sparker records north of Heceta Head indicate the northern Oregon continental shelf is mantled by a thin veneer of sediment, generally less than 20 m thick.

Kulm and Peterson's (in press) Holocene sediment isopach map depicts a portion of the southernmost part of the northern portion of the study area. They report that the unconsolidated sediment package they map is of Holocene or latest Pleistocene age, because it shows little or no deformation in high-resolution seismic records. These authors cite the lack of adequate seismic data as the reason for not continuing their work further north. The distribution of Holocene sediment in the southernmost part of the northern portion of the study area is described as a relatively thick accumulation which thins seaward toward Heceta Bank. Maximum sediment thickness is greater than 33 m. Heceta Bank is generally devoid of Holocene cover.

3.1.6 Specific Features Judged to Have the Greatest Potential for Prehistoric Occupation

Coastal sedimentation and the resultant landforms in the study area have been influenced by the effects of climate, eustatic sea level changes, preexisting onshore and offshore geology and geomorphology, and tectonic patterns throughout the Quaternary. Climate has largely controlled the glacio-eustatic rise in sea level during the Holocene, while the volume of glacial ice and the gradient of the continental shelf largely controlled the rate of sea level rise. Preexisting onshore geology and geomorphology have, most importantly, controlled major drainage patterns. Preexisting offshore geology has controlled subtle structures upon which Holocene shelf sediments rest. Tectonic patterns control the type and rate of shelf subsidence or emergence.

Before describing specific landform features, it is important to understand the nature of the subaerially exposed shelf starting at the beginning of the Holocene Transgression. The shoreline and coastal physiography of the study area at the beginning of the Holocene Transgression was radically different than that of today.

Sea level at the Wisconsin-aged glacial maximum lowstand was nearly 120 m below the present level. The shoreline position was located near the modern shelf break, and consequently very little continental shelf existed. The coastal plain had previously been leveled by repeated Pleistocene glacio-eustatic transgressions and regressions. The exposed early Holocene coastal plain (the continental shelf of the previous high stand) was likely characterized by a smooth, gently sloping surface dissected by meandering, low-gradient streams. Shoreface retreat during previous marine transgressions apparently eroded and redistributed a considerable amount of soil from the subaerial surface that once covered the uplands. The streams would have flowed into large coastal margin lakes and estuarine systems. Although much of the coarse-grained fluvial sediment became trapped in estuaries, a portion was distributed both onto the coastal plain by flood, fluvial channel, and crevasse splay processes, and out into the marine environment where a portion returned to the standline as beach and possibly extensive coastal plain dune deposits.

As the sea level quickly advanced landward during the early Holocene, the shoreline and previous coastal plain sediments were reworked into an erosional transgressive sand sheet. The erosive nature of the transgression destroyed much of the previously established coastal plain environment, at elevations above subsequent wave base. With the amount of sand available, the transgressive sea, and the low relief and shallow gradient of the continental shelf, it is possible that a barrier bar coastline was established along portions of the study area (Peterson, 1989, personal communication).

Between 10,000 and 7,500 B.P. the rate of sea level rise slowed due to the disappearance of the continental ice sheets. During the early Holocene, the continental shelf had widened at the expense of the previously leveled surface upon which the coastal plain deposits accumulated. With the decreased rate of sea level rise, shoreline environments had a longer time to achieve an equilibrium state. From as early as approximately 7,500-5,000 B.P., coastal erosion began to shape the modern shoreline. Actually, there is abundant evidence suggesting much of the present coastline morphology was inherited from the previous high stand. For example, narrow terrace deposits, submerged wave-cut platforms, and notched headlands all suggest the modern sea level position has reoccupied the previous high-stand position of many coastal sites (Peterson, in preparation).

Although the modern Texas Gulf coast belongs to a different climatic, oceanic and tectonic region, the Pleistocene-leveled coastal plain may well be considered a modern analog to at least a portion of the early Holocene coastal margin of the study area. Both areas share several common features including: low-relief shallow gradient coastal plain, smooth gentle offshore ramp, meandering fluvial systems drowning into coastal estuaries, adequate supply of sand, and a coastal environment necessary for reworking sediments.

Portions of the early Holocene coast of the study area that were not characterized by a barred coast (Texas Gulf coast analog) were most likely similar in appearance to the modern southern Florida coast. Although none of the U.S. west coast is built on a carbonate platform, certain morphological similarities are shared between the study area and the southern Florida coast including: a low-relief, shallow-gradient coastal plain and a smooth, gentle, energy-dissipating offshore ramp. The offshore ramp (the continental shelf) of the early Holocene coast of the study area was much narrower than that of the southern Florida model, and consequently wave energy was probably higher. In addition, the northwest Pacific coast has one of the highest wave energies in the northern hemisphere. Regardless of a specific modern analog, the early Holocene coast was characterized by a narrow shelf and a sand-rich, low-relief coastal plain. The early Holocene coastal and continental margin physiography of the study area is much different than today's coastal setting.

A partial list of specific, relict, geological features that may have existed along the late Pleistocene/Holocene subaerial coastal margin of the study area include: upland deposits, fluvial terraces, wave-cut terraces, meander plains, deltaic plains, coastal lakes, and beach and barrier complexes. A partial list of specific, relict, geological features that may have existed along the continental shelf of the study area include: estuaries, bays, subaqueous deltaic complexes, bay head deltas, distributary channels, islands, sea stacks, submarine banks, shoals, submarine terraces, shelf-edge bulges, escarpments, submarine channels, and paleo-shorelines (still stands).

Relatively few of these relict geologic features have survived intact because of the erosive nature of the Holocene Transgression. Even fewer of these features are recognizable in a large-scale, regional baseline study such as this. An attempt was made to identify and/or predict the positions of the more obvious features and then plot them on the 1:250,000 paleo-landform maps. It should be emphasized that relict geologic features are largely inferred from bathymetry, available seismic and subsurface data, structure, and general geologic trends defined onshore and extrapolated offshore. Not all favorable geologic features have been identified in this report. Not all cultural resources will be found at specific features judged to have the greatest potential for prehistoric occupation.

The more obvious features include: paleo-shoreline positions at 18,000, 15,000, 10,000 and 7,500 B.P.; islands, submarine canyons, submerged river valley systems, large faults, and headlands. A discussion of paleo-shorelines is included in Section 3.1.4 of this volume. Island

identification was based upon modern and paleo-bathymetric data. Shelf break submarine canyons were identified using modern bathymetric data.

The greatest amount of landform interpretation was employed while attempting to identify submerged river valley systems. It was assumed that the location of major Holocene-aged fluvial systems coincided with their present courses. During the mid-Wisconsin low stand, these fluvial systems flowed across the low-relief coastal plain in wide meander belts to the heads of some of the more prominent submarine canyons. During the subsequent Holocene Transgression, these channel systems have been at least partially eroded and subsequently filled with sediments. As a result, little or no surficial expression exists. The courses of these meander belts are subject to speculation. The meander belts themselves at least partially contain the most probable locations for large coastal plain lakes, estuaries, and bays.

Larger faults were identified from modern sea floor and onshore geologic data. Possible headlands extending seaward beyond calculated shoreline position were identified by both surficial geology and bathymetric data. The faults may have controlled fluvial courses and paleo-headland positions on the continental shelf (Peterson, 1990, personal communication).

The following text describes specific features of the 1:250,000 paleo-landform maps, included as Volume V of this report, for the study area between Cape Flattery, Washington, and Heceta Head, Oregon.

Starting to the north, the Cape Flattery, Washington, paleo-landform map exhibits a complex 18,000 B.P. paleo-shoreline reflecting the shallow nature and thin sediment cover of the continental shelf. The 7,500 B.P. shoreline is plotted within 1 km of the present coastline. Although no islands were identified between the 18,000 and 7,500 B.P. shorelines a number of large islands exist seaward of the 18,000 B.P. shoreline. Paleo-shoreline data indicate that modern nearshore islands were once part of the mainland. Only one shelf break submarine canyon, the Juan de Fuca Canyon, was identified. A large portion of the shelf is "drained" by tributary canyons connecting to the head of the Juan de Fuca Canyon. No major rivers drain this portion of the Olympic Peninsula, and consequently only two paleo-meander belt courses are identified. Suitably scaled bathymetric data could not be found west of longitude 125°21'W.

The Copalis Beach, Washington, paleo-landform map exhibits paleo-shoreline positions that trend parallel to both the modern coast and shelf break. The 7,500 B.P. shoreline is plotted within 2 km of the present coastline. No large islands were identified off any of the plotted paleo-shorelines. Several large shelf break submarine canyons occur off the coast of central and southern Washington including: Quinault, Grays, Guide, Willapa, and Astoria (figures II-9 and II-10). Additionally, several smaller shelf break canyons exist along this portion of the coast. A number of large- and medium-sized rivers flow into the marine environment along the central and southern portion of the Washington coast. The assumed seaward extension of these rivers across the continental shelf have been plotted on the paleo-landform map. These interpreted submerged river valley courses would be the most likely locations for relict estuaries and bays.

The Vancouver, Washington, paleo-landform map exhibits paleo-shoreline positions that again trend parallel to both the modern coast and shelf break. The 7,500 B.P. shoreline is plotted within 1 km of the present coastline. No large islands were identified off any of the plotted paleo-shorelines. This part of the shelf is conspicuously devoid of large shelf break submarine canyons. A number of medium-sized rivers flow into the ocean along this portion of the Oregon coast. The seaward extension of these ancient rivers at least partially cross the modern continental shelf. The end points of these submarine channels are uncertain because of the absence of associated submarine shelf break canyons. Again it is likely that any ancient bays and estuaries to

be found along this portion of the coast should be contained within these submerged river valley courses.

The southernmost sheet of the northern portion of the study area (the Salem, Oregon, sheet) exhibits a deviation to the paleo-shoreline pattern observed further north. The 18,000 and 15,000 B.P. shorelines deviate from their coast-parallel trend to a southwestern trend as they wrap around Heceta Bank. The 18,000 B.P. shoreline forms a peninsula extending south from the mainland, partially protecting a large bay to the east. Several large islands are defined by the 15,000 B.P. shoreline where the preceding peninsula existed. One small island occurs in the northern portion of the sheet off the 10,000 B.P. shoreline. The 7,500 B.P. shoreline is plotted within 1 km of the present coast. Several small islands occur nearshore of the 7,500 B.P. shoreline. Several possible prominent rocky headlands are defined as occurring in the 7,500 B.P. shoreline plot. Similar to the Vancouver, Washington, shelf, the northern and central Oregon shelf is conspicuously devoid of large submarine canyons. A number of medium-sized rivers flow into the ocean along this portion of the Oregon coast, and the seaward extension of these ancient rivers at least partially crosses the modern continental shelf. The end points of these submarine channels have been queried because of the absence of associated submarine shelf break canyons. It is again likely that ancient bays and estuaries found along this portion of the coast are contained within these submarine channels.

Besides reviewing paleo-landforms and attempting to identify likely locations of possible cultural resources, it is important to consider the preservation potential related to Holocene sediment thickness. In areas devoid of Holocene sediment, the likelihood of cultural resource preservation is judged to be extremely low due mainly to the high-energy nature of the Pacific coast. What is more, the erosive nature of the Holocene Transgression would effectively destroy most any cultural feature. In coastal regions, preservation is assumed to be most probable in sheltered areas such as wave-energy shadows created behind nearshore islands, low-energy protected estuaries, and low-energy back-barrier areas. Preservation of cultural resources also is assumed to be more probable in areas inland from the former coastlines that were buried by coastal plain fluvial, paludal, lacustrine, or eolian sedimentation. However, in order to preserve any coastal plain cultural resource, the rate of sedimentation would need to be enough to bury the resource below the encroaching, erosive shoreface of the Holocene Transgression.

While reviewing the paleo-landforms identified in this report, researchers should consider Holocene sediment thickness, distribution and most importantly, depth below subsequent transgressive wave base. Holocene cultural resources have the best likelihood for preservation in areas that accumulated Holocene sediments. Paleo-landforms identified in this portion of the study area that are devoid of Holocene sediment are unlikely targets for cultural resource preservation.

3.2 Heceta Head, Oregon (44°N) to Cape Mendocino, California (40°N 30'N)

3.2.1 Delineation of Area

As noted previously, the width of the continental shelf from Cape Flattery, Washington, south to Heceta Head, Oregon (44°N), averages 40 km (Figure II-14). South of Heceta Head, the continental shelf of southern Oregon and northern California narrows to an average width of less than 25 km. South of Cape Mendocino, California (40°30'N), the continental shelf narrows once again, defining the southern boundary of the southern Oregon/northern California region of the study area. The change in shelf width west of Cape Mendocino coincides with the location of the Juan de Fuca (Gorda), North American, and Pacific plate triple junction.

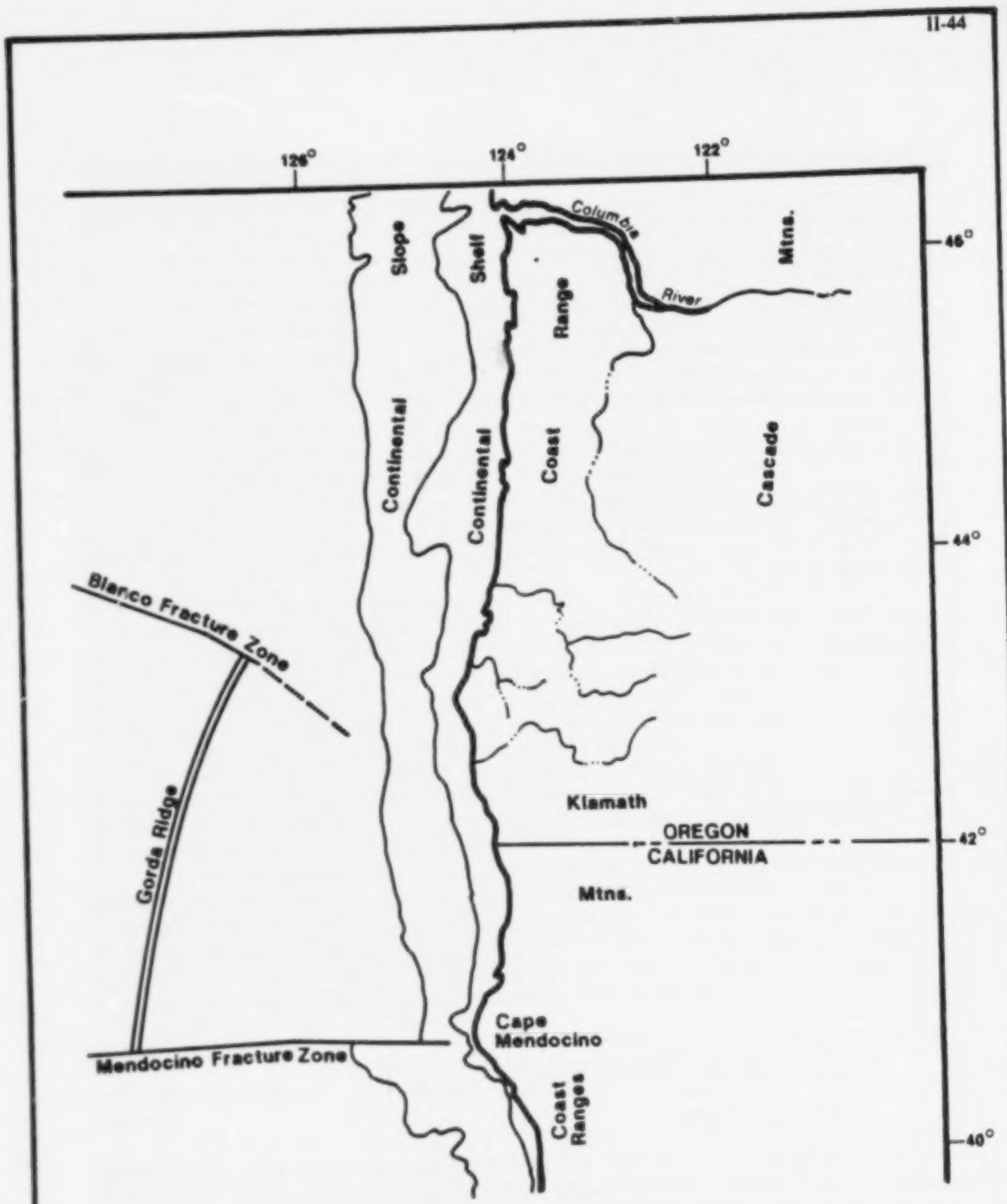


Figure II-14. Location of the Heceta Head, Oregon (44 degrees north), to Cape Mendocino, California (40 degrees, 30'N), Portion of the Study Area (from Kulm and Fowler, 1974 and Norris and Webb, 1976).

3.2.2 *Regional Setting*

3.2.2.1 Coastal Physiography

The coastal physiography of the central portion of the study area is a southern extension of the coastal physiography to the north, described in Section 3.1.2.1. The modern coast varies considerably in topography and is relatively straight and unprotected.

Starting to the north, the central and southern Oregon coast lies west of the Coast Range and Klamath Mountains and is characterized by resistant, rocky headlands, steep coastal cliffs, numerous sea stacks, several small isolated bays and estuaries, and sand beaches and dune fields as much as 5 km wide accreted to a narrow coastal plain. Elevated, wave-cut terraces are generally well developed in width and at least partially preserved. Several rivers draining the Coast Range cross the dune fields as shallow, narrow estuaries. One large estuary, Coos Bay, is also located along this portion of the coast.

The northernmost portion of the California coast is very similar to that of the southern Oregon coast with the exception of the Pelican Bay/Crescent City area (41°50'N). The Pelican Bay area is a broad, low-relief dune complex accreted onto the narrow coastal plain. The Smith River drains a portion of the Klamath Mountains and crosses the dune fields as a shallow estuary.

South of Trinidad Head, California (41°5'N), the coastal terrace is less rugged, and a low-relief, extensive coastal plain has developed at the mouth of the Eel and Mad rivers. However, just inland of this sandy, coastal plain, the topography is characteristically very steep. The Eel and Mad river coastal plain is dissected by meandering rivers and streams. The only major estuary in this portion of the study area is Humboldt Bay.

South of the Eel and Mad river coastal plain, the Cape Mendocino area is once again characterized by steep, rugged topography, rocky headlands, numerous sea stacks, and small isolated pocket beaches.

3.2.2.2 Tectonic History and Setting

Similar to the northern portion of the study area, the geologic history of the coastal margin and continental shelf of Heceta Head, Oregon, to Cape Mendocino, California, has been largely controlled by the collision of the Juan de Fuca (Gorda) and North America plates during the Cenozoic Era (Figure II-15).

The Blanco and Mendocino fracture zones lie directly west of southern Oregon and northern California. The Blanco fracture zone is a right-lateral transform fault, which offsets the Juan de Fuca spreading ridge to the north from the Gorda spreading ridge to the south. The right-lateral transform Mendocino fracture zone separates the Pacific plate from the Gorda plate and marks the sourthern termination of the Gorda spreading ridge. The oceanic area immediately north of the Mendocino fracture zone is described as one of active spreading (Atwater, 1970; Couch, 1980). The tectonic activity has affected the continental margin off northern California and southern Oregon (Spigai, 1970).

The Mendocino triple junction is a dominant tectonic feature and marks the southern boundary of the central portion of the study area. The Mendocino triple junction results from the collision of the Pacific-Farallon ridge with the North American plate during late Oligocene time (Atwater, 1970). The collision created two triple junctions, which migrated north and south with the growth of the intervening San Andreas transform fault system. The Mendocino triple junction is the northern feature and defines the location of the contact between the North American,

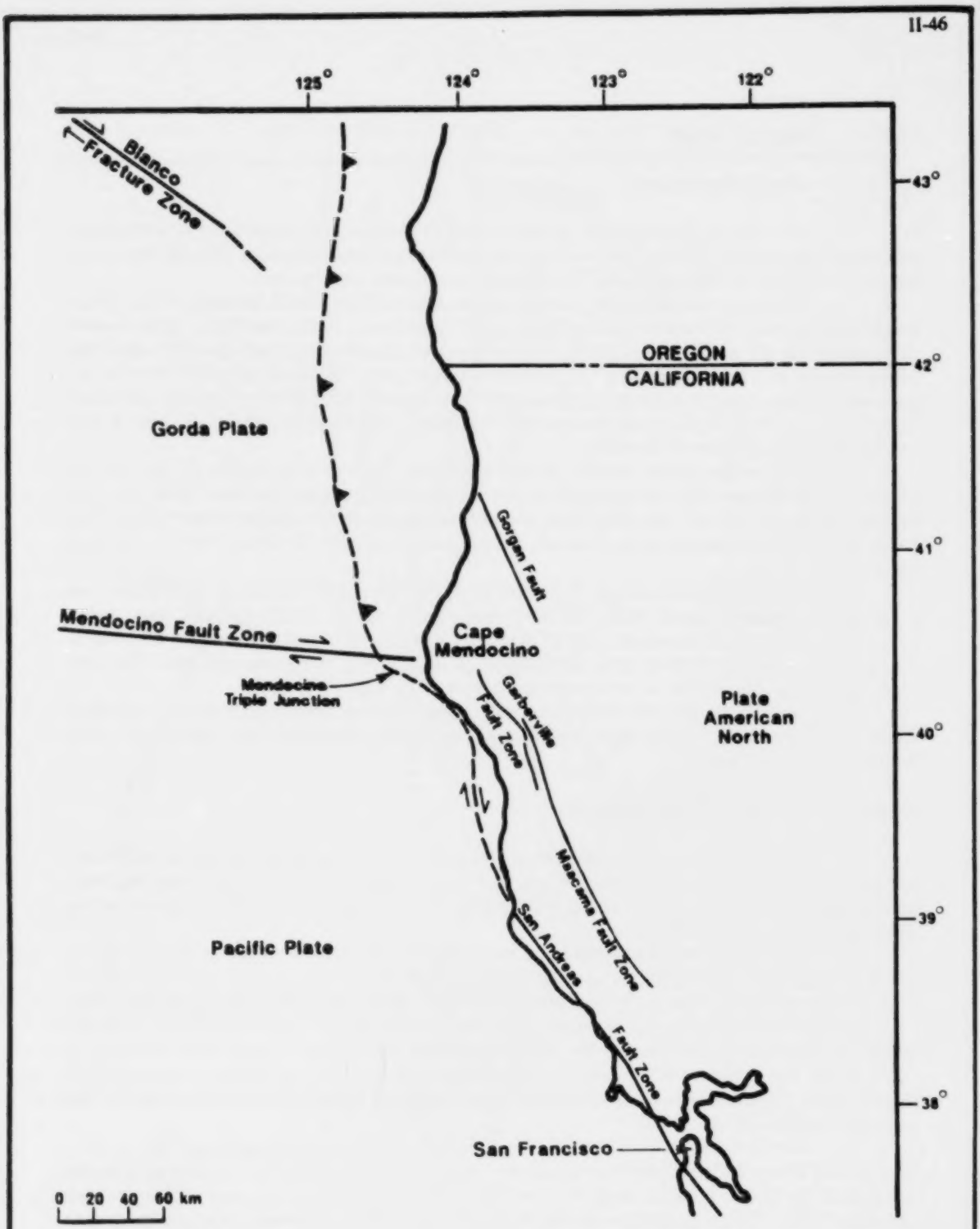


Figure II-15. Generalized Tectonic Map of Northern California (modified from Kelsey and Carver, 1988).

Gorda, and Pacific plates (Figure II-14). Atwater (1970) and Silver (1971) define the triple junction at the juncture of the San Andreas fault and the Mendocino Escarpment.

Dott (1971) reported that strain created by the transform boundary (non-spreading San Andreas fault zone) has been propagated at least 300 km north of the triple junction along the margin of the North American continental plate. More recently, Kelsey and Carver (1988) described strain patterns associated with the Mendocino triple junction as exhibiting a systematic evolution. Late Quaternary faulting affecting northern coastal California near Humboldt Bay is described as the southernmost extension of forearc contraction within the Cascadia subduction zone. The contraction results from the convergent plate coupling and has been moving northward preceding the northward migration of the triple junction. Kelsey and Carver (1988) suggest that as the triple junction continues to move north, the San Andreas strike-slip system will extend north-northwestward and contractional structures to the south will become inactive.

Kelsey and Carver (1988) conclude that crustal deformation in northern California and southern Oregon during the Quaternary Period resulted from the geometric instability of the Mendocino triple junction as it migrated northward. Dickinson and Snyder (1979) suggest that this type of instability results in the formation of extensional basins near the triple junction and landward jumps of the transform margin. Kelsey and Carver (1988) conclude that Quaternary subduction of the internally contracting Gorda plate probably most strongly influences crustal deformation of the continental and coastal margins north of Cape Mendocino.

Recent overthrusting of the North American plate onto the Gorda plate combined with the right-lateral slip along both the Mendocino and Blanco fracture zones have produced a strong compressive stress component that is principally oriented north-south to northwest-southeast (Couch, 1980; Simila, 1980). Moore and Silver (1968) describe recent deformation north of the Mendocino fracture zone which has produced predominantly northwest-trending folds in late Cenozoic strata. This northwest structural orientation is coincidental to the structural trends in the Coast Range south of the Mendocino fracture zone.

3.2.2.3 Shelf Physiography

Introductory comments reported in Section 3.1.2.3 concerning the general shelf physiographic controls of tectonics, sea level rise, stream gradient, sediment supply, coastal energy, and shelf/shoreline configuration during Quaternary transgressions also hold true for the central portion of the study area.

Southern Oregon Shelf

Similar to coastal physiology, the continental shelf off the southern Oregon coast appears to be a narrower extension of the previously described northern Oregon shelf. South of Heceta Bank, the shelf parallels the north-south-trending coastline, ranges from less than 15 to over 50 km wide, and averages nearly 25 km in width (Kulm et al., 1968). The shelf break generally occurs between 120 to 200 m depth (Spigai, 1970). The continental shelf off southern Oregon is narrower, deeper, and steeper than the world average shelf described by Shepard (1963).

The Oregon continental shelf is conspicuously lacking in number of large submarine canyons. Astoria Canyon to the north is assocated with the Columbia River drainage. The only significant submarine canyon cutting the continental shelf in southern Oregon is the Rogue Canyon, which is located 22 km northwest of the Rogue River and heads at a depth of 140 m (see paleo-landform maps). As in the continental shelf to the north, a number of smaller canyons and valleys cross the continental margin off southern Oregon.

The continental shelf extends seaward from the straight, but rugged, southern Oregon coastline as a gently sloping plain. However, Mackay (1969) describes the southern Oregon shelf north of the Rogue River as being only partially covered by a thin veneer of unconsolidated sediment. Chambers (1968) reported meandering bathymetric contours on the shelf, indicating bedrock exposures and thin sediment cover mimicking underlying structure. Bedrock exposures, such as the Rogue River and Blanco reefs, result from pre-existing structure, differentiation weathering, and differences in sedimentation rates.

South of the Rogue River, the shelf is underlain by a shallow sedimentary basin, the Eel River Basin (Kulm and Fowler, 1974). Bathymetric contours are less distorted, indicating a thicker unconsolidated sediment cover.

Coquille Bank (43°N) is a prominent north-south-trending, asymmetric, doubly plunging anticline located on the outer continental shelf approximately 8 km west of Cape Blanco (Clarke et al., 1985). The bank is 15 km long and 5 km wide. The base of Coquille Bank occurs at nearly 180 m depth. Structural relief is 60 to 90 m above the surrounding shelf. Snavely et al. (1977) suggest that Coquille Bank is structurally controlled, similar to the larger banks to the north.

Northern California Shelf

The continental shelf off northern California appears similar to that of southern Oregon. It extends seaward from the coast 10 to 30 km as a remarkably smooth plain. The shelf break generally occurs at 180 m. The continental shelf off northern California is considerably narrower than the worldwide average (Griggs and Hein, 1980).

Two large submarine canyons are located west of the northern California coast (see paleo-landform maps). Trinity Canyon (41°10'N) actually heads below the shelf break on the continental slope at approximately 750 m depth. Eel Canyon (40°41'N) has incised the outer continental shelf, and heads at nearly 150 m depth. While Eel Canyon is steep, narrow, and meandering, Trinity Canyon is described as broad, bowl-shaped, and has developed a tributary network (Field et al., 1980).

The prominent east-west trending Mendocino Escarpment (40°25'N), the surface trace of the Mendocino fault zone, marks the southern boundary of the central portion of the study area. The escarpment exceeds 1,000 m of relief, extends more than 1,600 km, and coincides with the Mendocino fracture zone. The Mendocino Escarpment marks the northern termination of the San Andreas fault.

The continental shelf off northern California is relatively flat and featureless, and is the southern extension of the Eel River Basin. The Eel River Basin trends north to northwest, and extends north from south of Eureka, California, to the southern Oregon continental shelf. The basin and its onshore component, the Humboldt Basin, is 200 km long and up to 70 km wide (Richmond et al., 1981). South of Eel Canyon, the continental shelf is marked by numerous sea stacks, bedrock outcrops, and a thin veneer of unconsolidated sediment cover.

3.2.2.4 Geology

The continental and coastal margins of southern Oregon and northern California represent the eugeosynclinal, western portion of the Cordilleran mobile belt throughout most of the Paleozoic to late Cenozoic time (Dott, 1971). The area has been subjected to orogenic activity periodically from Jurassic time with the last major orogenic event extending from mid-Tertiary to the present.

The geologic history of the central portion of the study area has been primarily determined by the interaction between the North American, Gorda, and Pacific plates (Atwater, 1970; Kulm and Fowler, 1974; Snavely et al., 1977). The area has been subjected to long-term compressive stress associated with sea-floor spreading and subduction. Additionally, stress propagating from the slip movement along the San Andreas fracture zone has affected the northern California and perhaps the southern Oregon coast and shelf.

The Quaternary history of the southern Oregon and northern California portions of the study area is characterized by both climatic variations and tectonism resulting from the most recent orogenic event which began during the late Pliocene (Wagner et al., 1972). Tectonically controlled deformation varies according to character of the basement rock and the physiographic province. Southern and eastern California are underlain by granitic batholiths and crystalline metamorphic rocks known as the Sierran basement. Much of the Coast Range is underlain by a thick, slightly metamorphosed, eugeosynclinal succession referred to as the Franciscan Formation. Areas underlain by the Franciscan Formation, such as much of the central portion of the study area, exhibit deformation characteristic of crustal shortening, such as complex folding. Areas underlain by the Sierran basement exhibit deformation characteristic of crustal extension, such as high-angle faulting, breaking and tilting blocks tens of kilometers wide and hundreds of kilometers long, but showing little sign of internal deformation (Wahrhaftig and Birman, 1965).

Continental

Starting to the north, the western Coast Range of Oregon was described previously in Section 3.1.2.4 as composed of a thick sequence of mainly Tertiary sedimentary and volcanic rocks. The southern portion of the Oregon Coast Range consists predominantly of Eocene volcanic and sedimentary rocks with younger Mio-Pliocene and Quaternary formations present near Coos Bay and Cape Blanco (Spigai, 1970). The north-trending Coos Bay synclinorium is described by Beaulieu and Hughes (1975) as an area of crustal weakness containing numerous small synclines and anticlines centered near Coos Bay. Structures here are more pronounced than elsewhere in the Coast Range. The Middle Fork of the Coquille River (43°N) is generally considered the southern boundary of the Oregon Coast Range.

The Klamath Mountains are located in the extreme southwestern corner of Oregon and extend into northern California (Figure II-16). The Rogue River, Smith River, and short-course coastal rivers drain rugged hills and mountains with as much as 2,700 m relief. Rocks of the Klamath Mountains are much older than rocks of the Coast Range. Paleozoic and Mesozoic rocks composing the Klamath Mountains have been locally metamorphosed to schist, phyllite, and marble, and have been intruded by granitic rocks and serpentized ultrabasic rocks. Irwin (1966) describes the occurrence of rocks in the Klamath Mountains as concentric, rudely arcuate belts which he divides from east to west into: the eastern Klamath, central metamorphic, western Paleozic and Triassic, and western Jurassic. These belts represent four imbricated thrust sheets with the older to the east and successively younger to the west (Baldwin, 1976). Structural trends in the Klamath Mountains range from northwest to northeast.

The California Coast Ranges extend from the Oregon border south and west of the Klamath Mountains to the Santa Ynez River north of Santa Barbara. The basement rocks of the northern California Coast Range are described by Berland et al. (1972) as predominantly massive graywacke with some chert, basalt-greenstone, shale, limestone, and schist of the complexly deformed Franciscan complex. Overlying the Franciscan complex are Cenozoic strata composed mainly of a variety of marine and non-marine sedimentary and volcanic rocks (Wagner et al., 1972).

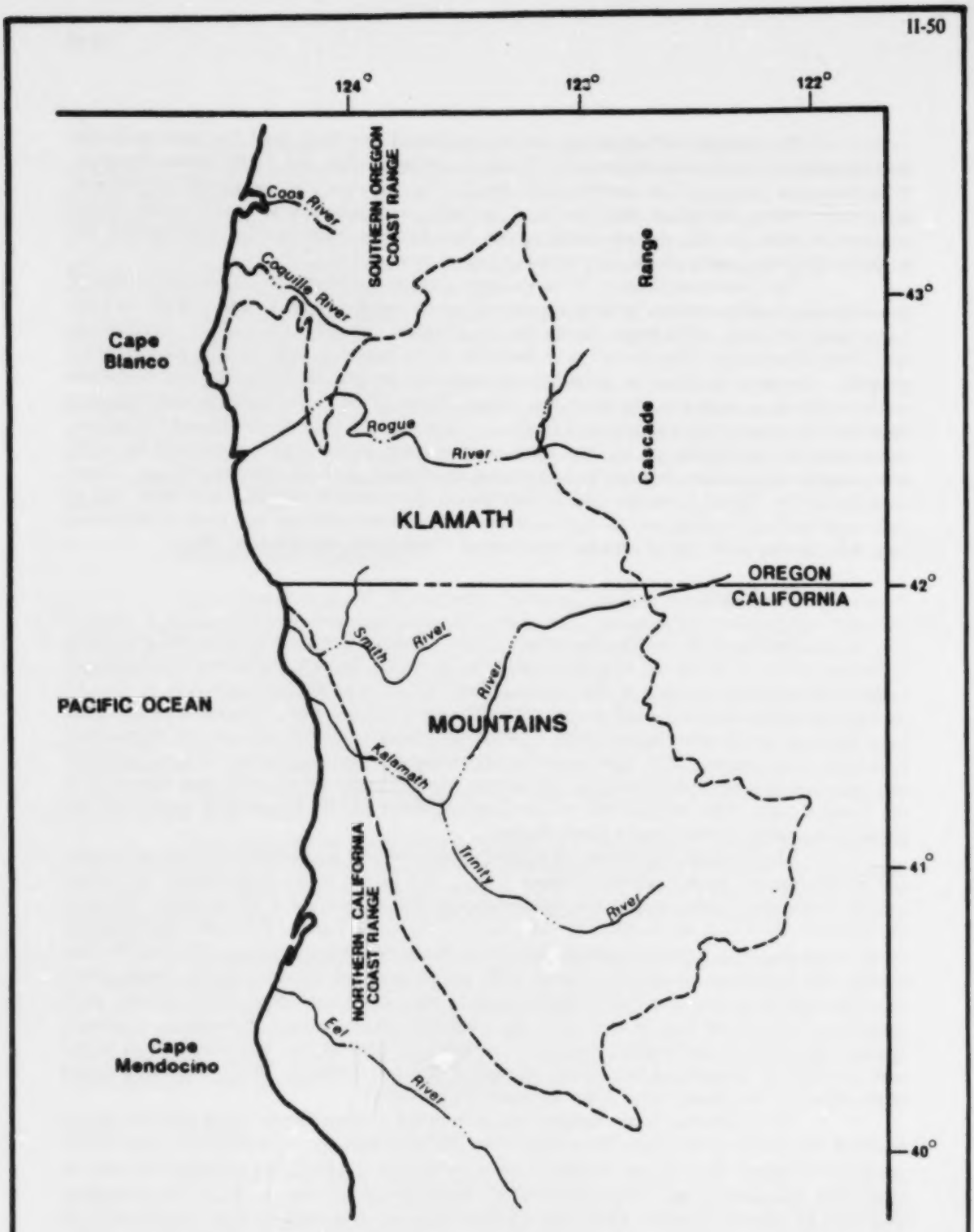


Figure II-16. Klamath Mountains Location Map (modified from Spigai, 1970).

The northern California Coast Range province exhibits a northwest to north structural trend, and is cut by numerous faults.

Oceanic

The geology and geologic history of the continental margin is directly or indirectly related to the adjacent continental geologic provinces (Spigai, 1970).

Starting to the north, Snavely et al. (1977) note that the majority of sedimentary and volcanic rocks found on the southern Oregon shelf range in age from Eocene to Pliocene. Mackay (1969) describes pre-Tertiary Jurassic and Cretaceous rocks off Bandon, Cape Blanco, and Gold Beach. Clarke et al. (1985) report that the north-trending Coos Bay Basin underlies the continental shelf between Heceta Bank and Coquille Bank. Coos Bay Basin contains greater than 5,000 m of middle Eocene and younger, principally marine, sedimentary rock.

Late to post-Pliocene tectonism uplifted an exposed Jurassic to middle-Tertiary basement rocks of the inner shelf. This tectonic event is also believed to have deformed Mio-Pliocene sediments into the gently undulating structures of the Coos Bay Synclinorium. Coquille Bank is also thought to have resulted from this period of deformation (Kulm et al., 1968). North-south-trending compressional folds and near-vertical faults down-dropped to the west characterize the southern Oregon continental margin (Spigai, 1970). Most of the older structures have been truncated and mantled with a veneer of Quaternary sediments.

The coastal margin off northern California and southernmost Oregon is an active depositional regime (Field et al., 1980). The Eel River Basin extends from south of Eureka, California, north to southernmost Oregon (Figure II-17). The Eel River Basin is one of five Miocene-aged basins found off the northern and central California coast.

The basins appear to be an extension of onshore Tertiary basins, and include, from north to south: Eel River, Point Arena, Bodega/Santa Cruz, Outer Santa Cruz, and Santa Maria (Wagner et al., 1972). These sedimentary basins trend northwest, and contain 1,500 to greater than 3,000 m of Neogene sediments. The basins were formed when outer shelf highs were uplifted (Keser, 1978), and subsidence of the inner continental shelf resulted in broad basins filled with shallow-water sediments.

Structural trends of the northern California continental shelf have undergone several intervals of Quaternary erosion and deposition. Wagner et al. (1972) attribute two causes for these events:

1) the previously described Pliocene-Recent orogeny, and

2) the Quaternary fluctuations in sea level brought on by glacial advances and retreats.

3.2.2.5 Oceanographic Setting

The oceanographic setting of the central portion of the study area appears to be controlled by the same regional forces determining water circulation patterns to the north. Also similar to the northern portion of the study area, oceanographic conditions prevailing over the southern Oregon and northern California continental margin change seasonally, primarily in response to variable wind patterns (Griggs and Hein, 1980). In addition to seasonal fluctuations, local eddies, deflections and current irregularities occur nearshore and are generally associated with promontories, embayments, and river mouths.

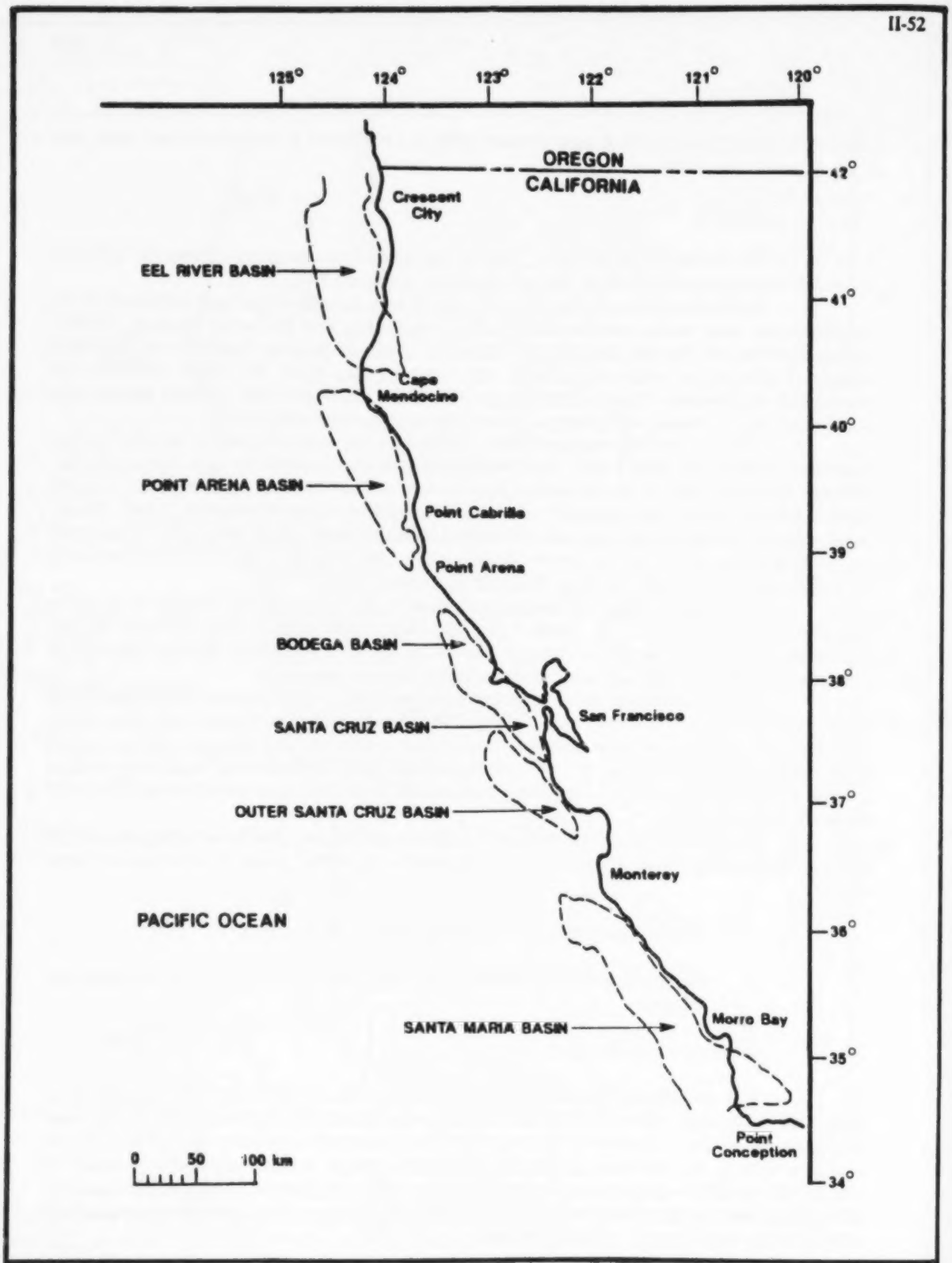


Figure II-17. Offshore Northern and Central California Basins (modified from Richmond et al., 1981).

During the summer months (July through November), the southerly flowing California current system dominates offshore water circulation patterns as winds along the coast are characteristically from the north and northwest. These northerly winds cause offshore Ekman transport, coastal upwelling, and a landward-sloping sea surface (Borgeld, 1985). The California current transports relatively cool water from the north, and is modified by temperature and salinity changes (Pirie and Stellar, 1977).

As summer ends, the overall wind pattern shifts. Southerly winds cause shoreward Ekman transport, a general coastal downwelling, and a seaward-sloping sea surface during the winter months of November to February (Borgeld, 1985). The counter current, the north-flowing Davidson current, then dominates the nearshore transport of water (Griggs and Hein, 1980).

From March to July, winds from the north generally parallel the shore and move water offshore, creating upwelling conditions (Griggs and Hein, 1980). Upwelling conditions are intensified near submarine canyons and south of capes and promontories that extend out into the coastal current system (Pirie and Stellar, 1977).

3.2.3 Representative Late Pleistocene/Holocene Stratigraphy

Similar to the northern portion of the study area, the Pleistocene/Holocene geologic history and stratigraphy of the central portion of the study area has been complicated by eustatic sea level changes and tectonism. This section will concentrate on the representative late Pleistocene and Holocene stratigraphy of the continental shelf and adjacent continental margin for the central portion of the study area from Heceta Head, Oregon, to Cape Mendocino, California.

3.2.3.1 Late Pleistocene/Holocene Differentiation

Although more data concerning Holocene sediment distribution and thickness were identified for the central portion of the study area relative to the northern portion, few investigations concerning the characteristics of surface sediments have been conducted along the southern Oregon and northern California continental margin (Field et al., 1980). Little is known of the type, areal extent, variation, and thickness of surface sediments along this portion of the continental margin. This scarcity of data can, again, perhaps be attributed to the lack of proven economic oil and gas targets occurring in nearshore sediments of the study area and associated in-depth research.

Horizontal reflectors overlying deformed and/or truncated beds found on the continental margin are thought to be unconsolidated, and are considered to be late Pleistocene to Holocene in age (Wagner et al., 1972). This unconsolidated section is again thought to be represented by an acoustically transparent unit.

Similar problems as previously described in Section 3.1.3.1 arise in attempting to differentiate the Holocene section from the older, underlying section, especially if that underlying section has not been deformed and is composed of a lithology similar to the overlying section.

3.2.3.2 Pleistocene Stratigraphy

Wahrhaftig and Birman (1965) report the Quaternary history of much of the onshore portion of the central region of the study area is one of erosion. A large influx of coarse-grained sediment was transported onto the continental margin during the Pleistocene as onshore erosion progressed. This influx was especially pronounced during lowstands of sea level when glaciation

and erosion were most active (Spigai, 1970). Pleistocene sediments off the southern Oregon and northern California coast are described as sand and silt interbedded with gravels (Snavely et al., 1977).

During the Pleistocene periods of lower sea stands, westerly flowing fluvial systems likely incised the exposed continental margin depositing sediments in floodplain, deltaic, and shallow marine environments. Sediments were then reworked into beach and shallow marine deposits which were reworked again during the subsequent transgression.

Pleistocene glaciation had a much smaller direct impact on the central portion of the study area compared to the northern region. Alpine glaciers formed in the Klamath Mountains and in a few of the higher peaks of the southern Oregon and northern California Coast Ranges. The shoreline has retreated and advanced across the continental shelf at least four times since the onset of Pleistocene glaciation (Bowman, 1972). These four cycles of transgression and regression coincide with the four glacial cycles recognized in the Pacific Northwest during the Pleistocene Epoch.

Wave-cut platforms developed along the coast during ancient still stands. These subsequently raised Pleistocene marine terraces occur discontinuously along much of the coast of the study area at elevations up to 400 m (Golder and Associates, 1986).

3.2.3.3 Holocene Stratigraphy

The most recent major regression affecting the study area started during the onset of Wisconsin glaciation approximately 30,000-35,000 B.P. As sea level dropped, the continental shelf was once again exposed and a late-Pleistocene erosional surface developed. The maximum late-Wisconsin lowstand was reached between 21,000 to 18,000 B.P. at approximately 120 to 130 m below the present level (Curray, 1965; Bloom et al., 1974).

The Holocene stratigraphy of the southern Oregon and northern California continental shelf represents deposits resulting from the eustatic sea level rise which began approximately 18,000 years ago in response to changes in the climate. From the onset of the Holocene transgression to about 10,000 to 7,500 years ago, a rapid inundation of the continental shelf occurred with minor regressions interrupting the general marine transgression. The rate of sea level rise has since slowed, and has been stable or fluctuating slightly during the past 3,000 years (Kulm et al., 1968).

As the Holocene transgression commenced and seas transgressed over the continental shelf, beach and near-shore sediments were presumably deposited ahead of the encroaching sea, forming a blanket sand deposit. Finer-grained silts and clays represent offshore, mid-shelf sediments deposited behind the advancing shoreline deposits (see Section 3.1.3.3).

As opposed to the much longer Pleistocene, where large volumes of coarse-grained sediments blanketed the continental margin, a much smaller amount of Holocene sediment reached offshore depositional sites (Spigai, 1970). Holocene sediments deposited on the continental shelf vary in thickness and consist mostly of unconsolidated sand, silt, clay, and gravels (Wagner et al., 1972).

The Holocene sediment distribution pattern on the southern Oregon and northern California continental margin is varied and irregular (Runge, 1965). The three facies of the Holocene Facies Model can be locally recognized, similar to the northern portion of the study area. They are:

1) nearshore sandy facies,
2) mid-shelf silt facies, and
3) outer-shelf relict sand deposit.

During the early portion of the Holocene Transgression, sedimentary facies were likely transitory in nature. There was possibly insufficient time for the deposition of the shelf facies to completely cover the basal transgressive sand.

The nearshore sandy facies represents the modern exposed position of the Holocene Transgression. Chambers (1968) recognizes sand off the Rogue River at depths up to 50 to 75 m, although sands deeper than 15 to 20 m may be relict sands of Pleistocene age. Welday and Williams (1975) report that surficial sediment distribution on the California shelf can be generally divided into a nearshore sand and mid- to outer-shelf silt and mud. The silt/sand boundary varies in depth along the northern California shelf from depths of 60 to 80 m.

The mid-shelf silt facies generally consists of silt and clay. The contact of the mid-shelf silt facies with the nearshore sand zone is gradational in nature. The mid-shelf silt facies extends to or beyond the shelf edge throughout most of the central portion of the study area. Interpretation of seismic records indicates the mid-shelf silt deposit thickens offshore of the mouths of larger rivers such as the Rogue and Eel rivers (Field et al., 1980).

Less relict sand is seen on the shelf edge in the central portion of the study area compared to the Cape Flattery to Heceta Head portion. Scattered deposits of gravel and sand occur on the outer shelf, and are considered to be mostly relict (Kulm et al., 1968). The lesser amount of relict sand may be attributed to the narrower width of the continental shelf from Heceta Head, Oregon, to Cape Mendocino, California. The mid-shelf silt deposits extend seaward to the shelf edge or beyond.

3.2.4 Sea Level Fluctuations

A generalized discussion of sea level fluctuations in the study area is included in Section 3.1.4. Similar to the adjoining coastal and continental margin to the north, the physiography of the Heceta Head to Cape Mendocino portion of the study area has been controlled by four major cycles of shoreline advance and retreat. During glacial periods, the shoreline retreated close to the edge of the modern continental shelf. During interglacial periods, the shoreline advanced to near modern levels. These changes in sea level occurred rapidly relative to geologic time and resulted in the formation of the broad, gently sloping, sediment-veneered, wave-cut platform which makes up the continental shelf of today.

The three sea level curves plotted on Figure II-13 can be used as generalized approximations of sea level rise during the Holocene.

Several Holocene sea level positions have been plotted on the paleo-landform maps attached to this report. The elevation of the individual Holocene sea levels were calculated using the same equation as in Section 3.1.4, considering tectonic adjustment.

In the central portion of the study area, Holocene sea level positions were plotted for 18,000, 15,000, 10,000, and 7,500 B.P. No younger sea level positions were plotted because of the proximity of the 7,500 B.P. position to the current-day shoreline.

Sea level rose at an average annual rate of >10 m/1,000 years until between 10,000 to 7,500 B.P. As the Wisconsin-aged continental ice sheets disappeared, the rate of sea level rise slowed to about 1.5 m/1,000 years for the remainder of the Holocene. Long-term sea level has remained relatively static for the past 3,000 years. Although the rate of post-glacial sea level rise

temporarily overwhelmed tectonic processes, the amount of tectonic uplift was considered in all sea level calculations.

While the entire coast of the Pacific Northwest has been subjected to tectonic uplift throughout the Quaternary (Golder and Associates, 1986), the central portion of the study area has experienced differential tectonic adjustment. From Heceta Head south to Cape Sebastian, Oregon (42°20'N), the average rate of tectonic uplift considered in the sea level equation was 0.4 m/1,000 years (Golder and Associates, 1986). From offshore Cape Sebastian, the Eel River Basin extends south for 200 km to near Cape Mendocino. The Eel River Basin extends from up to 50 km inland in the Humboldt-Arcata Bays area, offshore across the continental shelf and slope, averaging nearly 70 km in width. The basin is a major offshore depocenter containing nearly 5,000 m of Tertiary sedimentary section (Hoskins and Griffiths, 1971).

Borgeld (1985) and McLaughlin et al. (1983) report that the Eel River Basin has experienced an average tectonic subsidence rate of 2.8 m/1,000 years through at least the late Quaternary. An example of how this tectonic subsidence adjusted sea level position is provided below:

$H_{18,000\ B.P.} = h \pm h_o$, where

$H_{18,000\ B.P.}$ = present elevation of 18,000 B.P. shoreline,
h = sea level position extracted from Curray's (1965) generalized sea level curve at 18,000 B.P.,
h_o = (2.8 m/1,000 years) (18,000 years) = 50.4 m
$H_{18,000\ B.P.}$ = -125 m - 50.4 m = -175.4 m.

Both the rate and relative direction of the tectonic adjustment change near Cape Mendocino. As previously stated in Section 3.2.2.2, the Mendocino triple junction is a dominant tectonic feature of the study area that formed as a product of the collision of the Pacific-Farallon ridge with the North American plate during the late Oligocene. Crustal deformation in the northern California coastal margin during the past 3 million years results, in part, from the geometric instability of the triple junction. Although some researchers have reported uplift rates as high as 2.8 m/1,000 years to >4.0 m/1,000 years (Lajoie et al., 1979; Lajoie et al., 1982; Lajoie and Sarna-Wojcicki, 1982), the average rate of uplift for the Cape Mendocino coast is 1.0 m/1,000 years (McLaughlin et al., 1983).

3.2.5 Holocene Sediment Isopach Maps

The Holocene sediment isopach maps for the central portion of the study area contain the most complete data found in the entire project. Starting to the north, Kulm and Peterson's (in press) outstanding effort provides the first-order constraints on the thickness and distribution of Holocene sediment. Using both sparker and echo sounding data, the authors describe the Holocene seismic package as actually Holocene and/or latest Pleistocene sediments that are acoustically transparent and exhibit little or no deformation in high-resolution seismic records.

The Holocene sediment thickness north of Cape Blanco (42°50'N) is less than the area to the south. Most of the continental shelf north of Cape Blanco is covered with a thin-veneer patchwork of sediment, less than 16 m thick. Several small isolated pockets have accumulated thicker sediment, while in other areas, Tertiary sedimentary rock crops out on the shelf surface. The inner continental shelf between the Umpqua River (43°40'N) and Heceta Head exhibits a relatively thick wedge of late Pleistocene/Holocene unconsolidated sediment.

Kulm and Fowler (1974) describe the Holocene sediment distribution pattern between Cape Blanco south to the Rogue River (42°25'N) as characterized by a thick lens of unconsolidated material that parallels the modern coastline. Kulm et al. (1986) report the structure off the southern Oregon coast is characterized by north-south-trending compressional folds and steep faults. The troughs of the folds have ponded thicker accumulations of unconsolidated material.

The northern portion of the Eel River Basin lies off the coast of the Rogue River south to the state line. Three small north-south- to northwest-southeast-trending areas of thicker Holocene sediments occur on this portion of the shelf. However, the overall sediment distribution is thin.

Field et al. (1980) mapped the thickness and distribution of Holocene unconsolidated sediment on the northern California continental shelf. These authors caution that the Holocene/late Pleistocene contact is often subtle and that the exact age and degree of consolidation can only be determined, with any degree of assurance, by bore-hole studies. The majority of the northern California continental shelf is covered by at least 10 m of sediment. Two isolated depocenters occur off Humboldt Bay and southwest of Crescent City, California. Field et al. (1980) report the sediment off Humboldt Bay to be greater than 50 m thick, which may be the thickest accumulation seen in the entire study area. As in other portions of the coast, areas devoid of Holocene sediment include: offshore of rocky headlands, some submarine canyons, the innermost shelf, and some structural highs (Field et al., 1980).

3.2.6 Specific Features Judged to Have the Greatest Potential for Prehistoric Occupation

A lengthy review of coastal sedimentation and the resultant landforms in the study area was included in Section 3.1.6. The nature of, and processes controlling, the continental shelf and coastal margin morphology are similar for most of the study area. Please refer to that section as an introduction. The following text describes specific features depicted on the 1:250,000 paleo-landform maps included in Volume V of this report.

Starting to the north, the Coos Bay, Oregon, 2° paleo-landform map exhibits a continuation of the deviation established in the Salem, Oregon, map to the shore-parallel, paleo-shoreline pattern observed further north. Both the 18,000 and 15,000 B.P. shorelines wrap around the prominent, outer-shelf Heceta Bank. Directly south of Heceta Bank the paleo-shoreline once again conforms to a coast-parallel orientation. The 7,500 B.P. shoreline is plotted within 1 km of the present coast. Offshore of the Rogue River, the paleo-shoreline has been dashed to indicate a transition zone between tectonic regimes. The study area north of the Rogue River has experienced a tectonic emergence rate of 0.4 m/1,000 years, while the Eel River Basin south of the Rogue River has been subjected to a tectonic subsidence rate of 2.8 m/1,000 years. One small island is mapped off the 10,000 B.P. shoreline near Cape Blanco. A number of small islands are mapped off the 7,500 B.P. shoreline concentrated near Cape Blanco. Similar to the shelf further north, the southern Oregon shelf is conspicuously devoid of large submarine canyons. A number of large- to medium-sized rivers flow into the ocean along this portion of the Oregon coast, and the seaward extension of these ancient rivers at least partially crosses the modern continental shelf. The end points of these submarine channels have been queried because of the absence of associated submarine shelf break canyons. It is likely that ancient bays and estuaries to be found along this portion of the coast will be contained within these submarine channels.

The Crescent City, California, paleo-landform map exhibits paleo-shoreline positions that trend parallel to the present coast. The paleo-shoreline positions along this section of the continental shelf represent strandlines. The 18,000 and 15,000 B.P. paleo-shorelines are plotted seaward of the shelf break indicating either landward erosion or differential subsidence rates. The

7,500 B.P. shoreline is plotted within 5-7 km of the present shoreline. One small island and possible headland is mapped off the 10,000 B.P. shoreline near Point St. George (41°50'N). Several islands are plotted off the 7,500 B.P. shoreline concentrated near Point St. George. This was undoubtedly a major paleo-headland of lower sea level stands as indicated by bathymetric data and by heavy mineral accumulations. No prominent shelf break canyons occur in this portion of the study area. Two large- to medium-sized rivers flow into the ocean along this portion of the northern California coast, although recent sedimentation has obscured their paleo-course across the continental shelf. Again, it is likely that ancient bays and estuaries found along this portion of the coast are contained within these submarine channels or their extensions.

The southernmost sheet of the central portion of the study area (Eureka, California sheet) contains the southern extension of the Eel River Basin. Paleo-shoreline positions continue to parallel the modern coast. The 7,500 B.P. shoreline is plotted within 5 to 7 km of the present shoreline. South of the Eel River, the paleo-shorelines have been dashed to indicate a transition zone between tectonic regimes. While the Eel River Basin has experienced subsidence, the Cape Mendocino area has been subjected to the greatest amount of uplift of the entire study area (averaging 1.0 m/1,000 years). Near Cape Mendocino, the paleo-shorelines continue to parallel the present coast, but are plotted landward relative to those to the north. At Cape Mendocino, the 7,500 B.P. shoreline lies within 1 km of the coast. No large islands are plotted off the paleo-shorelines. An extensive possible headland is defined off the 7,500 B.P. shoreline near Bear River (40°30'N). The shelf break Eel River Canyon marks the southern end of the Eel River Basin. The paleo-course of both the Eel and Bear rivers has been plotted on the paleo-landform maps. These paleo-channel systems are coincident to the most likely locations of ancient bays and estuaries.

3.3 Cape Mendocino, California (40°30'N) to Morro Bay, California

3.3.1 Delineation of Area

The width of the continental shelf south of Cape Mendocino narrows considerably relative to the adjacent central portion of the study area (see Holocene Sediment Isopach Map). The change in shelf width west of Cape Mendocino coincides with the location of the Juan de Fuca (Gorda), North American, and Pacific plate triple junction, and marks the northern boundary of the southern portion of the study area. The southern portion of the study area extends over 800 km along offshore California (Figure II-18). The greater San Francisco Bay area will be described in Section 3.4.

3.3.2 Regional Setting

3.3.2.1 Coastal Physiography

The coastal physiography of the southern portion of the study area (Cape Mendocino, California, to Morro Bay, California) is a southern extension of the coastal physiography to the north, previously described in Section 3.2.2.1. The western coastal region of California is composed of four geomorphic provinces. These geomorphic provinces are from north to south: the Klamath Mountains, the northwest-trending Coast Ranges, the west-trending Transverse Ranges, and the northwest-trending Peninsular Ranges. The Coast Ranges extend nearly 900 km north to south and are divided by the San Francisco Bay. The entire southern portion of the study area lies within the Coast Ranges province.

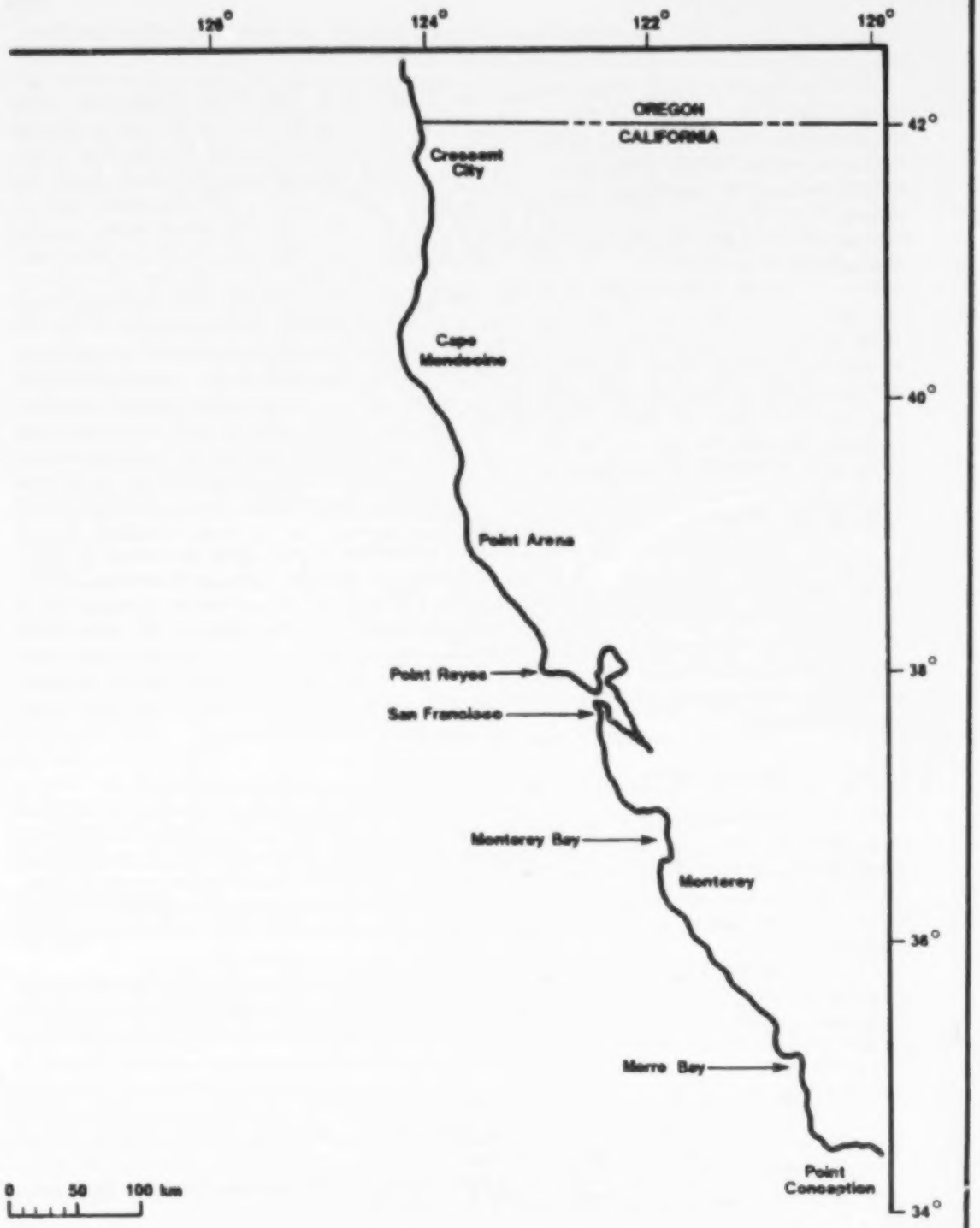


Figure II-18. Location Map of Cape Mendocino, California (40 degrees, 30'N), to Morro Bay, California, Portion of the Study Area.

The California coast between the Oregon border and Point Conception varies considerably in topography. Starting to the north, the stretch between Cape Mendocino and the Russian River (38°25'N) is generally mountainous. This portion of the Coast Ranges is comprised of the Mendocino Range. Most peaks in this portion of the Coast Ranges attain elevations of 900 to 1,100 m with the prominent peaks reaching nearly 1,300 m. The northern coastal region is characterized by a steep rocky coastline, a limited number of small isolated sand beaches, elevated marine terraces, and numerous small islands and sea stacks. No major rivers enter the ocean from this portion of the coast.

South of the Russian River, the coastal margin topography is more subdued than to the north, and is characterized by smaller, more-eroded mountains. From just north of the San Francisco Bay area to the south, the Coast Ranges split into four or five parallel ranges separated by structural valleys. The central coast between the Russian River and Carmel is more gentle, and is characterized by large embayments backed by broad coastal lowlands adjacent to San Francisco and Monterey Bays. Extensive sand beaches, elevated marine terraces and numerous steep bedrock cliffs mark the central coast. The most conspicuous geomorphic feature along this portion of the coast is the Point Reyes Headlands. From the granitic southwest terminus of Point Reyes, the headland widens in a shoreward direction and climbs to nearly 500 m. The northwestern coast of Point Reyes is marked by extensive dune fields.

South of Carmel, the coastal margin topography is once again dominated by steep, rugged mountains. The Santa Lucia Range composes the majority of this southernmost section of the study area. The Santa Lucia Range is nearly 225 km long and extends from Carmel south to the Cuyama River (35°N). The highest peak in the range is less than 1,800 m. The coast south of Carmel is characterized by a steep, rocky coastline, elevated marine terraces, small isolated sand beaches, and numerous small islands and sea stacks. This southernmost coastal portion contains perhaps the most dramatic coastline of the study area. Mountain peaks of over 1,000 m lie within 5 km of the coast.

3.3.2.2 Tectonic History and Setting

The Mendocino triple junction, described in Section 3.2.2.2, marks the northern boundary of the southern portion of the study area. South of the triple junction, the most dominant tectonic feature is the San Andreas fault zone. Unlike the northern and central portions, the southern portion of the study area is not directly influenced by convergent plate tectonism. Rather, the right-lateral, strike-slip motion of the San Andreas fault zone dominates regional tectonism.

The San Andreas fault zone is over 1,600 km in length, and strikes approximately northwest (N35°W) in a nearly straight trace through the Coast Ranges extending southeast to the Salton Sea. Oakeshott (1966) describes the long northwesterly trend as interrupted in only three places:

1) Cape Mendocino, where it turns abruptly to the west,
2) the southern terminus of the Coast Ranges, where the fault parallels the trend of the Transverse Range, and
3) the San Bernardino Mountains, where the fault changes direction again and continues southeast toward the Salton Sea.

Rather than a single fault, the San Andreas fault system generally consists of a fracture zone 1 to 5 km wide. This zone is composed of numerous, nearly parallel active faults, and

previously active older segments. The fracture zone is marked by fault gouge, breccia, geomorphic expressions, and disorganized jumbled fault blocks. Structural valley features have developed along the fracture zone, and serve as structural embayments (such as the Tomales Bay extension).

Researchers disagree upon the age of the San Andreas fault. Hill and Dibblee (1953) argued in their classic publication that the fault has exhibited displacement since the end of the Jurassic. Atwater (1970) argues that as long as the Farallon plate lay between the North American and Pacific plates, the San Andreas could not function as a strike-slip boundary. Thus modern strike-slip displacement between the two plates began no earlier than late Oligocene. However, Atwater (1970) concedes that it is possible that a pre-late Oligocene ancestral San Andreas fault could well have existed behind the middle-Tertiary trench as a trench-related strike-slip fault. Atwater (1970) also suggests that an ancestral San Andreas fault related to an earlier Tertiary episode of oblique motion could have existed.

The amount of displacement along the San Andreas fault is also subject to contention. Hill and Dibblee (1953) suggested the San Andreas has experienced over 550 km of displacement since the Jurassic. Recent movement along the fault has been substantial. Dibblee (1966) estimates between 32 and 64 km of movement since the middle Pliocene. Current displacement along the fault varies at different localities, but movement up to 3 cm/year and averaging 1.5 cm/year is common. The dominant motion of the San Andreas fracture zone can be described as right-lateral shear between the Pacific and North American plates.

Norris and Webb (1976) summarize a currently acceptable concensus regarding the type of movement along the San Andreas fault as follows:

1) "The San Andreas has had many periods of activity followed by quiescence.
2) Different parts of the fault have been active at different times.
3) No single section of the fault has a unique history.
4) Irregularity of movement over time has produced variety in rock deformation and geomorphism.
5) The conventional idea of a fault as an identifiable structure with similar characteristics throughout does not apply to the San Andreas."

Regardless of the age, amount of displacement, or fault characterization, the San Andreas has been the dominant Quaternary tectonic feature of the southern portion of the study area. The rocks and geomorphology of the coastal margin/continental shelf between Cape Mendocino and Morro Bay have both been strongly influenced by the San Andreas fracture zone.

3.3.2.3 Shelf Physiography

As reported in Section 3.1.2.3, the sedimentation, landform, and physiography of the coastal margin/continental shelf is chiefly controlled by the direction and rate of sea level change, coastal energy region, and the nature and amount of sediment input. In areas experiencing tectonic emergence, erosional transgression causes rapid cliff retreat resulting in the entrenchment of coastal streams. In areas of stability or tectonic subsidence, rising sea level results in the reworking of penecontemporaneous marine, eolian, and estuarine sediments exposed at the shoreface (Dupre, 1975).

The continental shelf from Cape Mendocino to Morro Bay is over 800 km long, and is considerably narrower than the worldwide average of 73 km (Shepard, 1963). The continental shelf meets the continental slope at a change of gradient marked between 125 and 200 m of depth.

The physiography of the continental shelf and the adjacent slope varies from north to south, and can be described by two end members and an intervening transition zone.

The northern end member, the continental shelf from Cape Mendocino to Point Sur (36°20'N), is described as a well-developed, gently sloping, smooth, erosional platform which varies in width from less than 10 to 50 km. The continental shelf off Cape Mendocino south to beyond Point Arena (39°N) is narrow, averaging less than 10 km in width. Several submarine canyons incising both the slope and the shelf head less than 2 km from shore. South of Point Arena to Point Sur, the shelf first widens to a maximum of nearly 50 km offshore of San Francisco before narrowing again to the south. Besides numerous nearshore bedrock exposures such as sea stacks, the only bedrock exposures on this portion of the shelf are the Farallon Islands. The most striking features of this portion of the continental shelf are the submarine canyons which include from north to south: Mendocino and Mattole (40°20'N), Spanish, Delgada, Noyo, and Monterey Canyons. Monterey Canyon, one of the world's largest, heads in Monterey Bay, dominates the submarine topography of offshore central California, and is composed of over ten branching tributaries which are described as steep-walled and narrow-floored (Greene et al., 1989).

The intervening transitional member occurs between Point Sur and Cape San Martin (35°55'N). Here the continental shelf is described as very narrow, averaging less than 5 km in width. This narrow shelf is adjacent to some of the steepest coastal topography of the study area. In the transition zone, the shelf/slope break is rather poorly defined at nearly 100 m.

The southern end member, the continental shelf from between Cape San Martin and Morro Bay, is described as narrow, averaging less than 10 km in width. McCulloch et al. (1980) describe this portion of the shelf as not exhibiting a well-developed shelf surface and, therefore, no well-developed shelf/slope break in topography. For purposes of this study the edge of the shelf is described as occurring between 100 and 130 m. Both the transition zone and the southern end member are also marked by numerous, nearshore sea stacks.

3.3.2.4 Geology

Much of the continental and coastal margin of northern and central California represent the eugeosynclinal, western portion of the Cordilleran mobile belt throughout most of the Paleozoic to late Cenozoic time. Two distinct underlying basement complexes at least partially control the structure of the southern portion of the study area. The dominant tectonic feature is the right-lateral, strike-slip San Andreas fault.

Four of the five previously listed Tertiary basins lie offshore of the southern portion of the study area, and compose much of the continental margin (Figure II-17).

Continental

The southern portion of the study area also belongs to the Coast Ranges Province. Two dissimilar basement or core complexes exist in this portion of the Coast Ranges. The two basement types are in contact along regional longitudinal faults. One of the basement types is the Franciscan complex which is composed of eugeosynclinal and basic intrusive rocks. The other is the Salinian block and is composed of metamorphic rock and granitic plutons (Norris and Webb, 1976) (Figure II-19).

Unlike the Salinian block, the Franciscan basement is described as a diverse assemblage of basement rocks lacking consistent systematic structure, regional metamorphism or intrusive granitic plutons. The Franciscan rocks have been variously labeled a series, formation, and assemblage (Norris and Webb, 1976), and should not be considered a sequence with ordinary

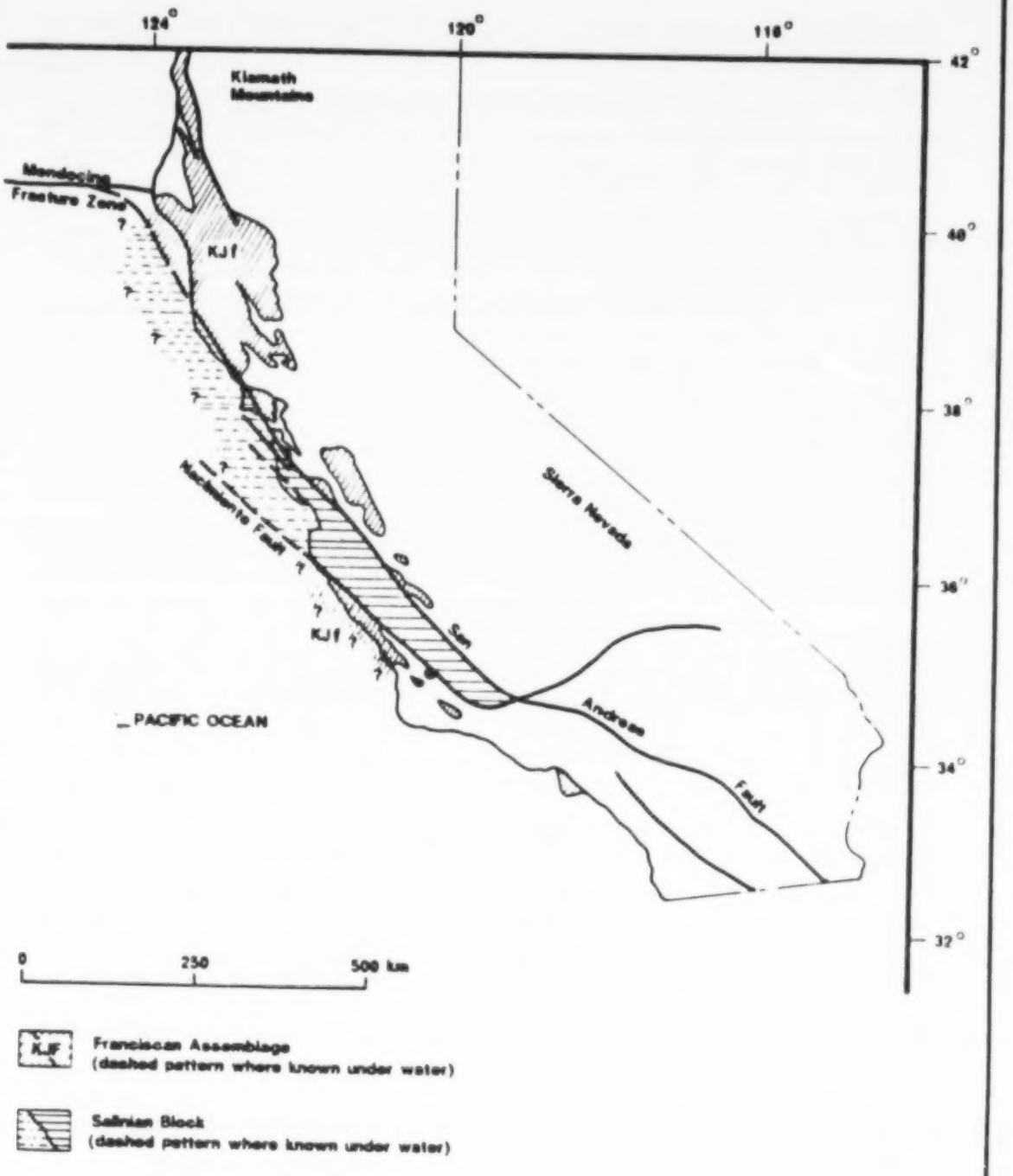


Figure II-19. Location of Franciscan Complex and Salinian Block Basements (modified from Rusnak, 1966).

physical, spatial, and temporal coherence. Rather, the Franciscan complex is best understood as a disorderly assemblage of various rock types that have experienced unsystematic disturbance (Page, 1966).

The Franciscan complex is dominated by graywackes typically deposited in deep marine basins by turbidity currents or submarine mud flows. The graywackes are interbedded with marine shale, chert, and limestone. In addition to these sedimentary rocks, the Franciscan complex contains some altered submarine volcanics that have generally been metamorphosed to greenstones and schists. The Franciscan complex has been intruded by ultrabasic igneous rock, now locally serpentinized. Rapid erosion rates of ultrabasic rocks along with high sediment yields in coastal rivers (such as the Eel and Russian) could possibly lead to spit/barrier bar development and associated estuary or lagoon settings.

The age of the Franciscan assemblage is uncertain. The scarce fossil content indicates the age ranges from late Jurassic through late Cretaceous (Page, 1966). Radiometric dating of associated ophiloite sequences indicate the complex is late Jurassic in age (Norris and Webb, 1976). With the innumerable tectonic displacements within the Franciscan complex, it is curious that no older rocks are in evidence. This curiosity is compounded by the presence of much older rocks in adjacent provinces. The situation has prompted the notion that Franciscan sediments were deposited in a deep oceanic trench directly overlying mantle material or on thin oceanic crust overlying the mantle (Norris and Webb, 1976). The serpentinized ultrabasic intrusions incorporated into the assemblage support that suggestion of proximal mantle association.

The Franciscan complex is thought to be over 15,000 m thick with no recognizable top or bottom. The areal extent of the Franciscan assemblage is over 200,000 km^2 on both land and continental margin (Norris and Webb, 1976).

The Salinian block is the second type of basement assemblage underlying part of the California Coast Ranges, and is composed of metamorphic rocks and granitic plutons. The metamorphic rocks of the Salinian block include gneiss, schist, quartzite, and marble locally referred to as the Sur Series in the Santa Lucia Range. Prior to metormorphism, these rocks were thought to be shelf or miogeosynclinal sandstones, shales, and carbonates. Granitic plutons extensively intruding the metamorphic terrain vary in composition from granodiorite and quartz monzonite to quartz diorite.

The age of the metamorphic assemblage is uncertain. Vague fossil evidence suggests the para-shelf and miogeosynclinal sequence is of at least Paleozoic age. The granitic plutons are radiometrically dated as Cretaceous through early Paleocene, and are younger than at least some of the Franciscan assemblage.

The Salinian block is bounded on two sides by the San Andreas and Nacimiento fault zones. The complex extends northwest offshore forming the basement beneath the central third of the central-northern California shelf (McCulloch et al., 1980). The granitic intrusions are widespread and probably underlie much of the Salinian block. The Salinian block is allothonous and are probably underlain by the Franciscan complex (Ross and McCulloch, 1979). Silver (1971) report that strike-slip faulting has displaced a sliver of Sierran-type granitic basement rock northwest up to 600 km, forming the Salinian block.

The northwest orientation of the Salinian basement block is reflected by the strong northwest structural trend exhibited throughout the Coast Ranges Province. The Coast Ranges are cut by numerous high-angle faults. The three most prominent faults are the San Andreas, Nacimiento, and South Fork Mountain faults.

The two unrelated basement complexes are covered by thick accumulations of late Cretaceous and Cenozoic sedimentary rocks. These younger rocks covering the basement consist mainly of marine and non-marine clastic sedimentary and volcanic sequences. The most extensive

deposit of the Coast Ranges is the Miocene Monterey Formation which is composed of marine sediments characterized by organic deposits and silicic phosphatic members (Norris and Webb, 1976).

Page (1966) summarizes the orogenic history of the Coast Ranges with four particularly important events. They are:

1) the early Cretaceous orogeny marked by granitic intrusions in the Salinian block,
2) the extensive early Tertiary(?) thrusting which juxtaposed Jurassic and Cretaceous sedimentary rock with Franciscan rock,
3) the continued Cenozoic strike-slip faulting of the San Andreas fault system, and
4) late Pliocene and Pleistocene folding and faulting.

Oceanic

The offshore geology of the southern portion of the study area appears to be an extension of the continental geology described in the previous section. McCulloch et al. (1977) suggest that the general tectonic style of the continental shelf appears related to the behavior of the underlying basement rocks. Although the basement beneath the overlying Cenozoic cover is not fully understood, onshore spatial relationships are thought to hold true offshore. Basement rock east of the San Andreas fault zone should be Franciscan assemblage while basement rock west of the San Andreas and east of the Nacimiento fault zone should be the metamorphic and granite sequence of the Salinian block. Evidence supporting this notion includes the Cretaceous-aged, granitic composition of the Farallon Islands and adjacent banks.

The strong northwest structural orientation exhibited onshore in the Coast Ranges appears to be carried offshore. The San Andreas fault zone trends northwest offshore from Point Arena. North of Point Delgada, the San Andreas fault continues to parallel the coast, deflecting to the west near the submarine Mattolle Canyon into the Mendocino fracture zone. The San Andreas fracture zone also trends northwest for a short distance offshore of the mouth of the Russian River, and for nearly 40 km between Bolinas Bay and the shoreline southwest of San Francisco. The trace of the Nacimiento fault zone appears to continue northwest offshore of Point Sur.

Subduction-related deformation dominated the offshore area in early and middle Tertiary time. In mid-Miocene time, a change in the pattern of deformation may have resulted from a change in the relative motion of the Pacific and North American plates (Silver, 1971), and initiated the formation of the Tertiary basins. Curray (1966) reports that outer-shelf margin ridges emerged to form the seaward margin of five Tertiary basins. These basins collected marine sediments more or less continuously until late Pliocene time (McCulloch et al., 1971). Quaternary deposition has been relatively limited.

The coastal margin of the southern portion of the study area contains four of the five nearshore Tertiary basins listed in Section 3.2.2.4 (see Figure II-17). Starting from the north, these four basins include: Point Arena, Bodega/Santa Cruz, outer Santa Cruz, and Santa Maria.

Point Arena Basin

The Point Arena Basin trends northwest, is approximately 140 km long, over 30 km wide in the south, and 55 km wide in the north. The eastern and northern boundaries of the basin are defined by the San Andreas fault zone as it deflects westwardly along the Mendocino

Escarpment. A Deep Sea Drilling Project corehole (DSDP Leg 18, Site 173, Kulm et al., 1973) located near the seaward marginal ridge encountered 320 m of Pleistocene through lower Miocene marine sediments before tagging basement rock. The basement underlying Cenozoic sediments appears complex. Hoskins and Griffiths (1971) report the basin to be underlain partly by pre-Cretaceous metasediments. McCulloch et al. (1977) report that Neogene structure is relatively simple to the north and rather complex to the south.

Bodega/Santa Cruz Basin

The Bodega/Santa Cruz Basin trends northwest, is approximately 180 km long, and has an average width of 25 km. Hoskins and Griffiths (1971) report the Bodega/Santa Cruz Basin overlies Salinian basement. Well data and the interpretation of gravity and magnetic data indicate granitic basement. The Bodega/Santa Cruz Basin contains over 5,000 m of marine sediment to the north and over 6,000 m of marine sediment to the south (Hoskins and Griffiths, 1971). Paleogene structure is complex, while Neogene structure is predominantly characterized by compression-forming structures parallel to the basin axis, and right-lateral shear along the San Andreas fault zone.

Outer Santa Cruz Basin

The outer Santa Cruz Basin also trends northwest across the continental shelf and upper slope. It is approximately 100 km long and 25 km wide. The basin is bordered to the northeast by the Pigeon Point High, a structural prominence that McCulloch et al. (1977) suggest is a probable southern extension of the quartz diorite cored Farallon High (Salinian basement?). The outer Santa Cruz High forms the southeastern border of the basin, and is composed of Franciscan rock or an early Tertiary equivalent (Silver, 1971). The outer Santa Cruz Basin appears to be on trend to the offshore portion of the Salinian block, and Hoskins and Griffiths (1971) suggested that the basin is underlain by granitic rocks (Salinian basement?). Several other researchers (McCulloch, 1973; Graham, 1976) have suggested that right-lateral strike-slip displacement may have offset the southern edge of the offshore Salinian block. McCulloch et al. (1980b) suggest that the Pigeon Point High actually represents the southwestern boundary of the offshore Salinian block, and the outer Santa Cruz Basin is underlain by Franciscan or Franciscan-equivalent rocks, rather than granite.

The outer Santa Cruz Basin is a relatively shallow Tertiary basin containing nearly 4,000 m of sediments (Hoskins and Griffiths, 1971), and thickens to the northwest. Paleogene sediments are dominated by marine sandstones which exhibit evidence of both deformation and erosion. The Neogene sediments are composed of shallow and deep marine sediments and volcanics dominated by the conspicuous Monterey Formation. The younger rocks of the outer Santa Cruz Basin are relatively devoid of Quaternary faults except in localized portions of the basin margin.

Santa Maria Basin

The Santa Maria Basin is the southernmost of the five Tertiary basins lying off the southern Oregon and California coasts. The Santa Maria Basin trends northwest parallel to the coast, and is approximately 230 km long and 40 km wide. Franciscan rocks of the shallow Santa Lucia High form the southwestern border, and the Franciscan basement elevated along major northwest-trending coastal faults forms the northeastern border. The Santa Maria Basin

extends northwest onto the continental slope, and southeast onshore north of Point Conception. Franciscan basement is thought to underlie the basement (McCulloch et al., 1980b; Page et al., 1979).

The distribution of Paleogene marine sediments in the basin is thought to be restricted by a late Paleogene unconformity to erosional remnants. The Neogene section is dominated by the Monterey Formation and subordinant marine sediments and volcanics. The sedimentary section of the Santa Maria Basin is thought to be over 3,000 m thick. The structural elements of the northern two-thirds of the basin trend northwest, while they trend north-south in the southern third. McCulloch et al. (1980b) report considerable evidence for Tertiary through Quaternary compression affecting the Santa Maria Basin.

3.3.2.5 Oceanographic Setting

The oceanographic setting of the southern portion of the study area appears to be at least partially controlled by the same regional forces determining water circulation patterns to the north. Also similar to the northern portions of the study area, oceanographic conditions prevailing over the northern and central California continental margin change seasonally, primarily in response to variable wind patterns (Griggs and Hein, 1980). In addition to seasonal fluctuations, local eddies, deflections and current irregularities occur nearshore generally associated with promontories, embayments, and river mouths.

During the summer months (July-November), the California current flows along the coast transporting relatively cool water from the north southward. The current is at least partially driven by predominant seasonal northerly and northwesterly winds. These winds cause offshore Ekman transport, coastal upwelling, and a landward-sloping sea surface (Borgeld, 1985).

As summer ends, the overall wind pattern changes. From November to February, north and northwest winds are weak or absent, and the north-flowing Davidson current dominates the nearshore transport of water. As seasonal southerly winds replace the northerly winds, a shoreward Ekman transport, general coastal downwelling, and a seaward-sloping sea surface develop (Borgeld, 1985).

From March until July, northerly winds start to redevelop the predominance of the California current. The Davidson current moves 10 to 30 km offshore while the California current moves further offshore. During particular portions of the year, counter-clockwise or clockwise gyres develop, especially near coastal promontories, resulting from the interaction between the California current and Davidson current.

3.3.3 Representative Late Pleistocene/Holocene Stratigraphy

Similar to the northern portions of the study area, the Pleistocene/Holocene geologic history and stratigraphy of the southern portion of the study area have been complicated by eustatic sea level changes and tectonism. This section will concentrate on the representative late Pleistocene and Holocene stratigraphy of the continental shelf and adjacent coastal margin for the southern portion of the study area from Cape Mendocino to Morro Bay, California.

3.3.3.1 Late Pleistocene Differentiation

As is true concerning the northern portion of the study area, a scarcity of data differentiating Holocene sediments from Pleistocene or older sediments and rocks was again encountered while searching both published and unpublished literature sources. Few investigations

concerning the characteristics of surface sediments have been conducted along the northern and central California continental margin, although a number of researchers have studied the Monterey Canyon area in detail (Chin et al., 1988; Mullins et al., 1985; Yancey, 1968).

Little is known of the type, areal extent, variation and thickness of surface sediments along the northern and central portions of the California continental margin. This scarcity of data can perhaps be attributed to the lack of proven economic oil and gas targets occurring in nearshore sediments of the study area and of associated in-depth research.

Horizontal sediments overlying deformed and/or truncated beds found on the continental margin are generally unconsolidated, and are considered to be late Pleistocene to Holocene in age (Wagner et al., 1972). This unconsolidated section is, again, thought to be represented by an acoustically transparent unit.

Problems similar to those described in Section 3.1.3.1 arise in attempting to differentiate the Holocene section from the older, underlying section, especially if that underlying section has not been deformed and is composed of a lithology similar to the overlying section.

3.3.3.2 Pleistocene Stratigraphy

Only the very highest peaks of the northernmost Coast Ranges were glaciated during the Pleistocene. Although the southern portion of the study area was not glaciated, a cooler and more humid environment prevailed. A greater amount of erosion occurred during this cooler, more humid climate, relative to today.

As noted in Section 3.2.3.2, Wahrhaftig and Birman (1965) report that the Quaternary history of much of the onshore portion of the California coast is characterized by erosion. A large influx of coarse-grained sediment was transported onto the continental shelf during the Pleistocene as onshore erosion progressed. Pleistocene sediments off the northern and central California coast are described as sand, silt, clay, and a minor amount of interbedded gravel (Kennedy et al., 1987).

Upper Pleistocene sediments deposited on the continental shelf of the southern portion of the study area were derived mainly from either the Franciscan or Salinian block core, or the overlying Cenozoic sedimentary cover of the Coast Ranges. Westerly flowing fluvial systems transported sediment derived from the Coast Ranges into coastal environments on the continental margin during lower stands of Pleistocene sea level. Sediment accumulated in westerly prograding deltaic systems which migrated in response to sea level fluctuations (Osborne et al., 1980). Sediments introduced through deltaic systems were reworked to form beach and shallow marine deposits. As sea level rose, erosional transgression reworked these marine, shoreline and coastal plain deposits.

Episodic Pleistocene glacial advances and retreats occurring to the north were accompanied by dramatic eustatic changes in sea level. Similar to the northern portions of the study area, the shoreline in northern and central California has retreated and advanced across the continental shelf at least four times since the onset of Pleistocene glaciation. These four cycles of transgression and regression coincide with the four glacial cycles recognized in the Pacific Northwest during the Pleistocene Epoch.

Wave-cut platforms developed along the coast during ancient still stands. These subsequently raised Pleistocene marine terraces occur discontinuously along much of the California coast.

3.3.3.3 Holocene Stratigraphy

The most recent major regression affecting the study area started during the onset of Wisconsin glaciation approximately 30,000-35,000 B.P. As sea level dropped, the continental shelf was once again exposed, and a late Pleistocene erosional surface developed. The maximum late-Wisconsin lowstand was reached between 21,000 to 18,000 B.P. at approximately 120 m below the present level (Curray, 1965; Bloom et al., 1974).

The Holocene stratigraphy of the northern and central California continental shelf represents deposits resulting from the eustatic sea level rise which begin 15,000 to 18,000 years ago in response to changes in the climate. From the onset of the Holocene Transgression to about 7,500 to 10,000 years ago, a rapid inundation of the continental shelf occurred with one regression interrupting the general marine transgression. The rate of sea level rise has since slowed, and has been stable or fluctuating slightly during the past 3,000 years (Kulm et al., 1968).

As the Holocene transgression commenced and seas transgressed over the continental shelf, beach and near-shore sediments were deposited ahead of the encroaching sea, forming a blanket sand deposit. Finer grained silts and clays represent offshore, mid-shelf sediments deposited behind the advancing shoreline deposits (see Section 3.1.3.3).

As opposed to the Pleistocene, where large volumes of coarse-grained sediments blanket the continental margin, a smaller amount of Holocene sediments reached offshore depositional sites due mainly to decreased onshore erosion and estuarine sediment trapping. Holocene sediments deposited on the continental shelf vary in thickness and consist mostly of unconsolidated sand, silt, clay, and a minor amount of interbedded gravel (Wagner et al., 1972; Kennedy et al., 1987).

The Holocene sediment distribution pattern on the northern and central California continental margin is varied and irregular. Except for the relict sand occurring in the Gulf of the Farallones off San Francisco, only two of the three members of the Holocene Facies Model can be regionally recognized on the continental shelf between Cape Mendocino and Point Reyes.

The nearshore sandy facies represents the modern exposed position of the Holocene Transgression. Welday and Williams (1975) report that surficial sediment distribution on the northern California shelf can be generally divided into a nearshore sand and mid- to outer-shelf silt and mud. The silt/sand boundary varies in depth along the northern California shelf from depths of 60 to 80 m.

North of Point Reyes, the mid-shelf silt facies generally consists of silt and clay. The landward contact of the mid-shelf silt facies with the nearshore sand zone is gradational in nature. The mid-shelf silt facies extends beyond the shelf edge throughout most of this part of northern California.

Over 80 percent of the sediment produced between the Oregon border and Point Conception is derived from these northern California rivers: Eel, Klamath-Trinity, Mad, Smith, and Mattole, and Redwood Creek (Griggs and Hein, 1980) (Figure II-20).

The Gulf of the Farallones from Point Reyes south to Point Año Nuevo contains the most extensive sand deposit of California's offshore region. Here, only relict sand occurs. The Sacramento and San Joaquin rivers have entered the Pacific Ocean through the San Francisco Bay system for more than one million years. These rivers carry mostly suspended, fine-grained sediments derived from 40 percent of the land area of California (Welday and Williams, 1975). Very little sand-sized material passes through the San Francisco Bay system due to estuarine trapping. Fine-grained sediments transported through the Golden Gate must be carried elsewhere such as stillwaters in the San Francisco Bay (carried back into the bay via tidal currents), quiet deep waters beyond the Farallones, or protected nearshore localities.

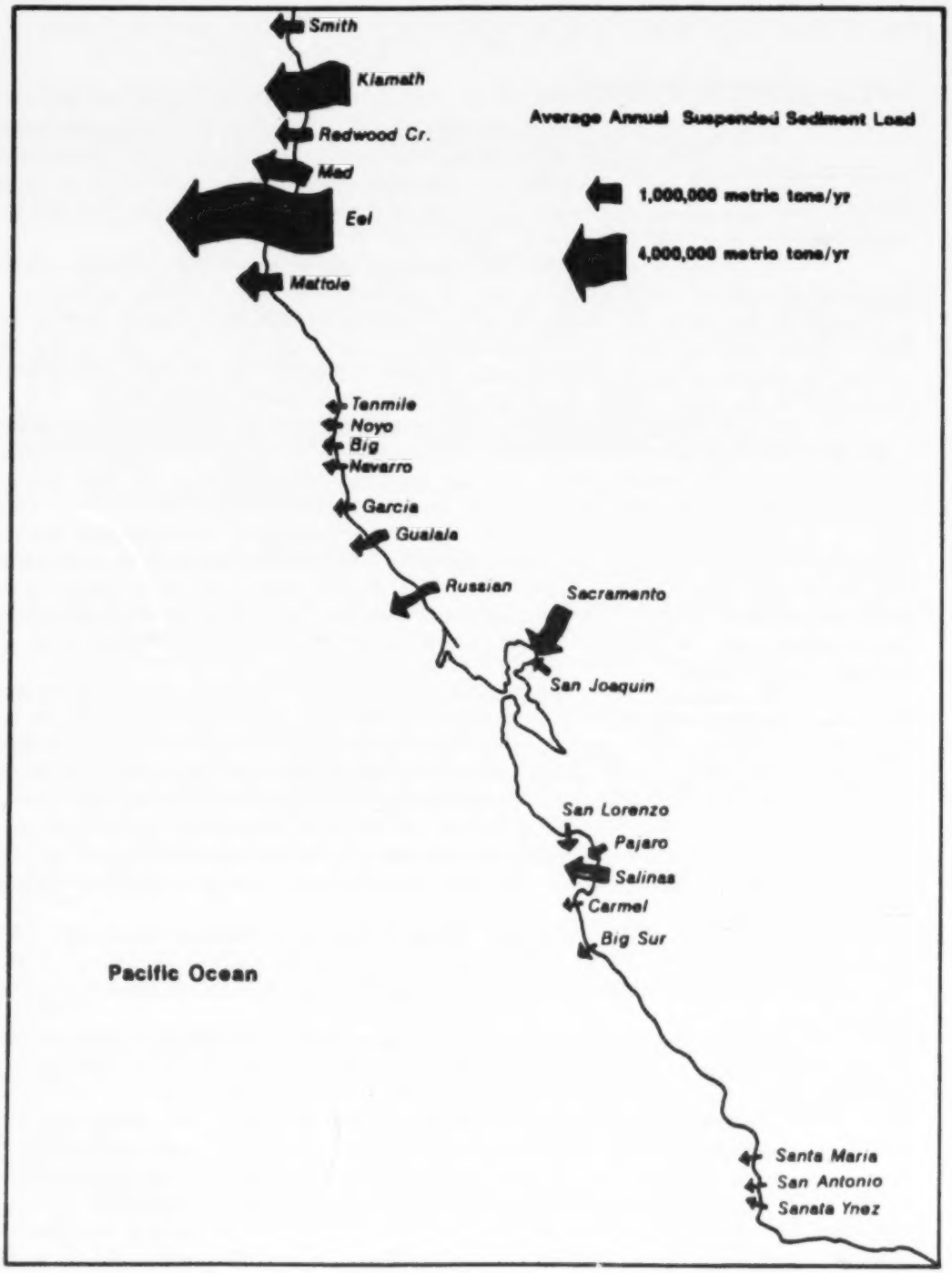


Figure II-20. Average Annual Discharge of Suspended Sediment from the Major Streams Between Point Conception and the Oregon Border (from Griggs and Hein, 1980).

The continental shelf south of the Gulf of the Farallones from Point Año Nuevo south to Carmel is dominated by the Monterey Canyon system. Both the nearshore sandy facies representing the modern exposed position of the Holocene Transgression, and the mid- to outer-shelf silt and mud facies can be recognized. The contact between the two is gradational and occurs between 40 and over 100 m of depth. The continental shelf in Monterey Bay in incised by a number of large continental slope-depth tributaries containing muddy Holocene sediments (Osborne et al., 1980).

South of Monterey Bay, the nearshore zone from shoreline down to nearly 30 m is generally described as rocky with only thin, patchy sediment cover (Welday and Williams, 1975). Seaward beyond this rocky zone, surficial sediments of the continental shelf and upper slope are composed primarily of relict sand. Neither the nearshore sand facies nor the mid-shelf silt facies of the Holocene Facies Model exists in this portion of the continental shelf. Griggs and Hein (1980) report that, from Monterey Bay to Point Conception, the coastal climate is drier than to the north, and sediment input is much reduced.

3.3.4 Sea Level Fluctuations

A generalized discussion of sea level fluctuations in the study area is included in Section 3.1.4. Similar to both the northern and central portions of the study area, the Cape Mendocino to Morro Bay section has been controlled by four major cycles of shoreline advance and retreat. During glacial periods, the shoreline retreated to near the edge of the modern continental shelf. During interglacial periods the shoreline advanced to near modern levels. These changes in sea level occurred rapidly relative to geologic time, and resulted in the formation of the broad, gently sloping, sediment-veneered, wave-cut platform which makes up the modern continental shelf.

Similar to the Pacific Northwest and northern California, no sea level curve specific to the southern portion of the study area was identified during the background literature and data search. The three sea level curves plotted on Figure II-13 can be used as generalized approximations of sea level rise during the Holocene.

Several Holocene sea level positions have been plotted on the paleo-landform maps attached to this report. The elevations of the individual Holocene sea levels were calculated using the same equation as in Section 3.1.4, considering tectonic adjustment.

In the southern portion of the study area, Holocene sea level positions were plotted for 18,000, 15,000, 10,000 and 7,500 B.P. No younger sea level positions were plotted because of the proximity of the 7,500 B.P. position to the current-day shoreline.

Although tectonic subsidence and uplift, and to a lesser extent glacio-isostatic rebound, strongly affected sea level positions in portions of the study area during the late Quaternary, eustatic sea level rose at an average annual rate of >10 m/1,000 years until between approximately 7,500 and 10,000 B.P. As the Wisconsin-aged continental ice sheets disappeared to the north, the rate of sea level rise slowed to about 1.5 m/1,000 years for much of the remainder of the Holocene. Long-term sea level has remained relatively static for the past 3,000 years. Although the rate of post-glacial sea level rise temporarily overwhelms tectonic processes, the amount of tectonic uplift or subsidence was considered in all sea level calculations.

The entire coast of the Pacific Northwest has been subjected to tectonic uplift throughout the Quaternary (Golder and Associates, 1986). Sections of the central portion of the study area experienced differential rates of uplift, while the Eel River Basin actually subsided through time. Near Cape Mendocino the tectonic adjustment of the study area changed from subsidence to the north to strong emergence resulting from plate interaction at the Mendocino

triple junction (McLaughlin et al., 1983). Although some researchers have reported uplift rates as high as 2.8 m/1,000 years to >4.0 m/1,000 years (Lajoie et al., 1979; Lajoie et al., 1982; Lajoie and Sarna-Wojcicki, 1982) the average rate of uplift for the Cape Mendocino coast is 1.0 m/1,000 years (McLaughlin et al., 1983).

This relatively high rate of emergence extends south some 65 km from Cape Mendocino to Whale Gulch, California (39°55'N). South of Whale Gulch, the rate of tectonic emergence for the California coast averages 0.3 m/1,000 years (Ku and Kern, 1974; McLaughlin et al., 1983, Muhs, 1985; Merritts and Vincent, 1989). An example of how this tectonic uplift adjusted sea level positions is provided below:

$H_{18,000\ B.P.} = h \pm h_o$, where

$H_{18,000\ B.P.}$ = present elevation of 18,000 B.P. shoreline,
h = sea level positions extracted from Curray's (1965) generalized sea level curve at 18,000 B.P.,
h_o = (0.3 m/1,000 years) (18,000 years) = 5.4 m
$H_{18,000\ B.P.}$ = -125 m + 5.4 m = -119.6 m.

3.3.5 Holocene Sediment Isopach Maps

More Holocene thickness data were found for the southern portion of the study area than the northern portion, but less than the central portion. Starting to the north, little Holocene thickness data were found for the Eureka, California, sheet south of Cape Mendocino. Wagner et al. (1972) completed an offshore geologic study to evaluate the feasibility of running an undersea pipeline from northern to southern California. In their work, they presented maps portraying the thickness of unconsolidated, nearsurface sediments covering much of the California continental shelf. Seismic reflection data were primarily utilized in mapping thickness and distribution trends. The unconsolidated sediment package was comprised of acoustically transparent, undeformed, late Pleistocene and Holocene material.

Unconsolidated sediment thickness data were found for a small area of the continental shelf between the Spanish and Delgada submarine canyons offshore of Shubrick Rock (40°05'N) in the Eureka, California, sheet. This area is characterized as a seaward-thickening wedge of material that attains a maximum thickness of over 100 m. More recent work indicates that the bottom of this interpreted sediment package may actually occur earlier in the Pleistocene, and that thickness data are therefore exaggerated (Field, M.C., 1989, personal communication).

Wagner et al.'s (1972) work covers most of the northern and southern portion of the Ukiah, California, sheet. No thickness data were found for the central portion of the Ukiah sheet near the submarine Noyo Canyon (39°35'N). The northern portion of the Ukiah sheet is characterized by a small, north-south trending, lens-shaped accumulation attaining a maximum thickness of over 100 m. Much of the inner shelf and mid-shelf is devoid of sediment cover. Extrapolating isopach contours into the central portion of the Ukiah sheet suggests thin sediment cover. The southern portion of the sheet is portrayed by an irregular distribution of late Pleistocene/Holocene sediments that are generally oriented north-south. Although Wagner et al. (1972) report that the unconsolidated late Pleistocene/Holocene sediment thickness on the Ukiah, California, continental shelf attains values >100 m, the actual Holocene thickness is more likely on the order of 15 to 35 m.

Unconsolidated late Pleistocene/Holocene sediment thickness on the continental shelf of the Santa Rosa, California, sheet is characterized by a large shore-parallel depocenter (Wagner

et al., 1972). This accumulation attains a maximum thickness of over 150 m west of Bodega Head (38°20'N). Similar to the northern areas, the nearshore, inner shelf regions are generally devoid of sediment cover. Again, although Wagner et al. (1972) report that sediment thickness on the Santa Rosa portion of the continental shelf attains values >150 m, the actual Holocene thickness is more likely on the order of 15 to 50 m.

No data were identified concerning Holocene sediment thickness on the continental shelf for the northern half of the San Francisco, California, sheet. However, this portion of the continental shelf, the Gulf of the Farallons, contains the most extensive sand deposit of California's offshore region (Welday and Williams, 1975). Only very thin, isolated patches of Holocene sediment cover this relict sand deposit. South of Point San Pedro (37°35'N) the Holocene sediment thickness of the continental shelf is described by McCulloch et al. (1980), who define Holocene sediment as a thin, acoustically transparent unit of unconsolidated material overlying another thin unit of unconsolidated sediment. Holocene sediments form two distinct wedges which thin seaward against the shelf edge at Pigeon Point High. These depocenters parallel both the shelf break and coastline, and attain a maximum thickness of 15 to 20 m. The nearshore, inner shelf is generally devoid of sediment cover.

Little Holocene thickness data were found concerning the continental shelf of the Monterey, California, sheet. North of Monterey Canyon in Monterey Bay, Wagner et al. (1972) characterize the late Pleistocene/Holocene sediment distribution and thickness as a series of small isolated, shore-parallel pockets of sediment accumulation. The thickest sediment accumulation of this portion of the continental shelf is described as less than 20 m. Actual Holocene sediment thickness is probably even less. Chin et al. (1988) describe a small portion of the continental shelf south of Monterey Canyon. Maximum late Pleistocene/Holocene sediment thickness is estimated to be less than 35 m. The rocky headland of the Monterey Peninsula, the southern border of Monterey Bay, is devoid of sediment cover. South of the Monterey Peninsula, a small, but relatively wide, protrusion of the continental shelf occurs off Point Sur. Although no thickness data could be found for this portion of the shelf, Welday and Williams' (1975) map suggests thin sediment cover. The continental shelf south of Pfeiffer Point (36°15'N) is extremely narrow, and no thickness data could be found. The inner portion of this narrow shelf is devoid of sediment cover, while the remainder is expected to be covered by a thin patchwork veneer.

No Holocene thickness data could be found for the San Luis Obispo, California, sheet of the study area. However, the inner shelf appears rocky and devoid of sediment cover (Welday and Williams, 1975). The remainder of the shelf is expected to be covered by a thin patchwork veneer of unconsolidated sediment. Sediment thickness is estimated to range between 0 and 15 m.

3.3.6 Specific Features Judged to Have the Greatest Potential For Prehistoric Occupation

A lengthy review of coastal sedimentation and the resultant landforms in the study area was included in Section 3.1.6. The nature and processes controlling the continental shelf and coastal margin morphology are similar for most of the study area. Please refer to that section as an introduction. The following text describes specific features of the 1:250,000 paleo-landform maps included in Volume V of this report.

Starting to the north in the Eureka, California, sheet, the Cape Mendocino area has been subjected to the greatest amount of tectonic emergence of the entire study area (averaging 1.0 m/1,000 years). The continental shelf is rather narrow along this portion of the coast. Near Cape Mendocino, the paleo-shorelines parallel the shelf break and approximate the orientation of the coast. The 7,500 B.P. shoreline in the southern half of the Eureka, California, sheet lies within

1 km of the present coastline. Several small islands were identified lying off the 10,000 and 7,500 B.P. shorelines. A number of large shelf break canyons were also identified including: Mendocino, Mattole, Spanish, and Delgada. The heads of both Mattole and Delgada canyons have incised the continental shelf to within 2 km of the present coastline. Although no large rivers flow into the ocean along this portion of the northern California coast, the landward extensions of these canyons may contain inactive, buried channel systems and associated bays and estuaries.

The Ukiah, California, paleo-landform map exhibits paleo-shoreline positions that trend parallel to both the modern coast and the shelf break. The dashed portion of the paleo-shorelines to the north represent a transition zone between tectonic regimes. To the north, the Cape Mendocino area has experienced uplift at an average rate of 1.0 m/1,000 years, while south of Whale Gulch the average rate of tectonic emergence for the California coastal margin is estimated to be 0.3 m/1,000 years. The 7,500 B.P. paleo-shoreline lies within 1 km of the present coast. Several small- to medium-sized islands were identified off the 15,000, 10,000, and 7,500 B.P. shorelines. Three shelf break canyons were also identified: Noyo, Navarro, and Arena. A number of medium-sized rivers enter the ocean along this portion of the coast. The seaward extension of these rivers across the continental shelf has been plotted on the paleo-landform map. These paleo-channel systems are coincident to the most likely locations of ancient bays and estuaries.

The Santa Rosa, California, paleo-landform map exhibits paleo-shorelines that trend parallel to the modern coastline. The 18,000 B.P. lowstand, however, is more closely oriented parallel to the shelf break, and wraps around Cordell Bank in the southern portion of the area. The 7,500 B.P. shoreline lies within 1 km of the coast. Several small islands are identified off the 7,500 and 15,000 B.P. shoreline. Bathymetric data indicate that Cordell Bank was a large-scale mainland promontory during the late-Pleistocene Wisconsin lowstand, and a large outer shelf island at 15,000 B.P. Possible headlands were identified near Point Arena at 7,500 and 10,000 B.P. One unnamed submarine canyon was identified in the shelf break re-entrant east of Cordell Bank. The seaward extension of the Russian River and a possible fluvial system west of Bodega Bay were plotted on the paleo-landform map. It is possible that ancient bays and estuaries to be found along this portion of the coast will be contained within these submarine river valleys or their extensions.

The 7,500 and 10,000 B.P. paleo-shorelines of the San Francisco, California, sheet parallel the present coastline. The 7,500 and 10,000 B.P. paleo-shorelines near the Golden Gate are dashed due to inference, and a change in the rate and nature of tectonic adjustment. The 7,500 B.P. shoreline lies within 2 km of the coast. The 15,000 and 18,000 B.P. paleo-shorelines are plotted parallel to the shelf break on the mid-shelf to outer shelf. The only islands of note that exist off the plotted paleo-shorelines are the outer shelf Farrallon Islands. Several shelf break canyons are plotted on the map. No major rivers directly enter the ocean along this portion of the central California coast. However, the seaward extension of the Golden Gate drainage is plotted on the paleo-landform map.

Similar to the San Francisco sheet, the 7,500 and 10,000 B.P. paleo-shorelines of the Monterey, California, sheet parallel the present coastline. The 7,500 B.P. shoreline lies within 1 km of the coast. The 15,000 and 18,000 B.P. shorelines are plotted parallel to the shelf break on the mid-shelf to outer shelf. Several small islands are plotted off the 7,500, 10,000 and 15,000 B.P. shorelines. The shelf break off the Monterey coast is dominated by a number of large submarine canyons. The heads of a number of these canyons have incised the shelf to within several kilometers of the coast. Previously the paleo-course of larger rivers plotted across the shelf were identified as likely locations for ancient bays and estuaries. Since the heads of many of the submarine canyons occur very near the present shoreline, the paleo-course of the rivers across the shelf is limited. However, landward extensions of several of the distal shelf break canyons may coincide with ancient bays and estuaries.

The continental shelf of the southernmost sheet of the study area, the San Luis Obispo, California, sheet, is characterized as narrow and rocky. The paleo-shorelines parallel both the modern coast and the shelf break. The 7,500 B.P. shoreline lies within 2 km of the coastline. A number of small islands were identified off the 15,000, 10,000 and most notably the 7,500 B.P. paleo-shorelines. Several shelf break canyons were identified. Although no large rivers flow into the ocean along this portion of the central California coast, a number of smaller rivers drain this onshore portion of the study area. The landward extension of the shelf break canyons and the seaward extension of the coastal drainages are likely locations for ancient bays and estuaries.

3.4 Greater San Francisco Bay Area

3.4.1 Delineation of Area

The San Francisco Bay region, for the purpose of this study, includes both the San Francisco and San Pablo bays which extend from Sunnyvale to the south to the western end of the Carquinez Strait to the north. The bay is the largest estuary on the California coast and consists of 2,030 km^2 of open water and tidal flats (Helley et al., 1979). The bay lies between north-trending ridges with the San Francisco and Marin peninsulas to the west and the Berkeley Hills to the east. The Sacramento and San Jaoquin rivers are the major sources of fresh water and alluvial sediment to the bay. Both are in the northern part of the bay. In the south bay area are the less significant Coyote Creek and Guadalupe River.

3.4.2 Regional Setting

3.4.2.1 San Francisco Bay Physiography

Physiographically the bay has been characterized as consisting of numerous islands, peninsulas, and small embayments that were formed by the rise in sea level during the last 10,000 years (Atwater et al., 1976). These features represent the submergence of former hills, valleys, ridges, and alluvial fans. The majority of the bay is shallow with water depths less than 3 m (Goldman, 1969). Deeper areas up to 110 m are present in the main channel under the Sacramento River. The Berkeley Hills to the east and the coast mountains to the west attain an elevation up to 1,200 m.

Four major constrictions exist in San Francisco/San Pablo bays; one at San Petro-San Pablo Point (at the Carquinez Straits) that is the southern narrowing of San Pablo Bay; another between San Francisco and Oakland that is the southern narrowing point of northern San Francisco Bay; the narrowing at the bay mouth at the location of the Golden Gate Bridge; and the last a smaller narrowing in the area of Dumbarton and Ravenswood points. These narrowing points affect both fresh- and salt-water currents and tides. These constrictions somewhat reflect the stages of inundation of the lowland areas during sea level rise in the last 10,000 years (Atwater et al., 1976). The rising sea first entered the Golden Gate 10,000 years ago and progressed inland at a rate of up to 30 m per year. The amount of lowland area encroached upon by the rising sea reflects how low and flat the basin of San Francisco Bay is. These constrictions may also have served as land bridges or crossing points for animals and man.

3.4.2.2 Tectonic History and Setting

The major tectonic element of the greater San Francisco Bay region is the San Andreas fault zone described previously in Section 3.3.2.2. The San Andreas fault zone separates Franciscan Formation basements to the east from Salinian block granites to the west. Helley et al. (1979) report San Francisco Bay did not exist as late as one million years ago. The Point Reyes Peninsula may have been located south of the present Golden Gate within the past several million years, with right lateral strike slip motion along the San Andreas fault zone subsequently displacing the granitic basement to the northwest.

The Hayward fault, which is located on the east side of the bay along the western foot of the Berkeley Hills, is part of the San Andreas fault zone. The Hayward fault is a right lateral strike-slip feature that has been active throughout the Pleistocene and Quaternary. The Hayward fault parallels the San Andreas fault and is coupled with the Calaveras fault. The Calaveras fault is thought to have been active up until the Pliocene-Pleistocene. The Hayward fault is currently active with surface displacement features visible in San Pablo Bay.

Prior to late Pleistocene time, the San Francisco Bay area experienced tectonic subsidence, filling with marine and terrestrial sediments. Quaternary tectonics and deformation are quite irregular in the San Francisco Bay area, evidenced by the fact that some locations are emerging while others are subsiding.

The greater San Francisco Bay area occupies a late Pliocene structural depression that has been inundated by several Quaternary eustatic marine high water stands. The greater bay complex has been at least partially flooded up to four times during interglacial periods. As the late Wisconsin ice sheet began to melt nearly 18,000 B.P. and release water into the oceans, sea level began its modern rise. The rising sea entered the Golden Gate area 11,000 to 10,000 years ago (Helley et al., 1979). Holocene marine incursion proceeded rapidly until between 7,500 and 5,000 years ago when eustatic shoreline advance slowed. Much of the subsequent sea level rise seen in the San Francisco Bay region is due to tectonic subsidence.

3.4.2.3 Geology

San Francisco Bay area is a mixture of sedimentary rocks that consist of the Mesozoic-age metamorphosed Franciscan assemblage to presently forming sediments. The Franciscan assemblage rock is present on the northwest, west, and south sides of the bay, in Marin County and on the San Francisco peninsula. Sedimentary Miocene and younger rocks form the basement on the east side of the bay.

The system of bays which includes the San Francisco, San Pablo, and Suisun bays has been flooded repeatedly since the Pliocene. One the thickest units of the area is the 1,370-m Pliocene-Pleistocene Merced Formation which consists of marine rocks capped with nonmarine lacustrine rocks. This stratigraphic succession indicates that sea level was falling, relative to land surface during the early Pleistocene. This trend was reversed during the Holocene, as will be discussed in the following sections.

3.4.2.4 Oceanographic Setting

Activities associated with the Pacific Ocean tides, wave action, and sea level changes have different effects on the San Francisco Bay system than on western shorelines because of the protection of the Marin and San Francisco peninsulas. Tidal influences create many of the currents in the San Francisco Bay system and there is a long lag time between tidal changes and

response in distal portions of the bay. Wave action is similarly affected, where only large tsunami-type waves would severely impact interior bay shorelines. Tsunami-generated impacts would be greatest immediately east of the Golden Gate, along the Berkeley-Emeryville coastline.

3.4.3 Representative Late Pleistocene/Holocene Stratigraphy

Similar to the remainder of the study area, the Pleistocene/Holocene geologic history of the greater San Francisco Bay area has been complicated by eustatic sea level changes and tectonism. Evidence of vertical crustal movement, both fluvial incision and deposition, and changing sea levels can be seen throughout the greater San Francisco Bay area.

3.4.3.1 Late Pleistocene/Holocene Differentiation

During Pleistocene glacial periods, the Pacific Ocean shoreline was located as far west as the Farallon Islands, and fluvial and alluvial conditions dominated the greater San Francisco Bay area. As Pleistocene glaciers melted, the rising sea periodically entered through the Golden Gate, inundating portions of the bay area, and estuarine conditions prevailed. During these high sea stands, estuarine sediments were deposited and wave-cut marine terraces were carved into the surrounding mountains and coastal areas. During low stands, erosion and eolian, alluvial and fluvial deposition prevailed. Discontinuous terrestrial deposits and erosional breaks separate estuarine deposits found throughout the greater San Francisco Bay area.

Late Pleistocene sediments are differentiated from Holocene sediments by a distinctive, but aerially limited, terrestrial sand unit (Merritt Sand) that overlies and interfingers the older estuarine muds. Where the sand unit is absent and evidence of an erosional break is obscure, differentiation is often accomplished by comparing physical properties of the units since their lithologic compositions are similar. The older estuarine muds contain less moisture than the overlying younger muds. The late Pleistocene muds are also more consolidated than the younger Holocene sediments (Goldman, 1969).

3.4.3.2 Pleistocene Stratigraphy

Atwater et al. (1976) describe the youngest known Pleistocene estuarine deposits found in the southern San Francisco Bay area as produced by Sangamon sea level high stands. They estimate the areal extent of the Sangamon estuary to be similar to that of the modern bay. Despite post-depositional erosion, Sangamon estuarine deposits can be found underlying most of the post-Wisconsin estuarine deposits. The size of this youngest Pleistocene estuary may have varied in response to sea level changes 130,000 to 70,000 years ago.

Although data from the Atlantic coast of the United States suggest sea level approached its modern position 40,000 to 30,000 years ago (Milliman and Emery, 1968), estuarine sediments of this age appear to be absent from at least the southern portion of the San Francisco Bay area (Atwater et al., 1976). Birkleland's (1972) work in coastal central and southern California supports the absence of a middle Wisconsin sea level high stand.

The youngest Pleistocene estuarine deposits are described by Goldman (1969) as firm, dark greenish-gray silty clays with varying amounts of sand and fine gravel principally found in stream channels incising older estuarine or basement units. The thickness of the youngest Pleistocene sediments varies from less than 1 m to greater than 60 m, and appears to increase in thickness towards the center of the bay.

The discontinuous late Pleistocene terrestrial sediments separating the late Pleistocene/Holocene estuarine muds are described as clay, silt, sand, gravel and occasional peats (Atwater et al., 1976). The alluvial sediments disconformably overlie Sangamon estuarine deposits and their thickness generally increases southeastward from less than 1 m to greater than 25 m between Menlo Park and Fremont. Alluvial sediments generally average less than 3 m thick. Depositional environments include alluvial fan and fluvial regimes. Peats are thought to record freshwater marsh conditions formed as base level rose in response to rising sea levels.

The eolian deposits overlie and locally interfinger older estuarine muds. These sandy sediments are thought to extend from the Golden Gate southeastward to at least the San Mateo area, and obtain a maximum thickness of 15 m near Oakland. Sands appear to be derived from floodplains and beaches on the broad continental shelf to the west that was exposed during lower sea level stands. The sands were transported east across low-lying portions of the San Francisco Peninsula and through the Golden Gate.

3.4.3.3 Holocene Stratigraphy

The Holocene estuarine deposits began to form shortly after the rising sea level entered the bay area through the Golden Gate 11,000 to 10,000 years ago (Helley et al., 1979) (Figure II-21). Inundating estuarine waters rapidly spread across the low-relief land. Estuarine enlargement slowed as the rate of sea level rise slowed 7,500 to 5,000 years ago. However, due to active tectonic subsidence, the estuary has continued to grow larger.

The Holocene estuarine muds are described as soft, dark gray-olive gray clay and silty clay with rare sand and gravel. The unit consists of 95 to 45% clay-sized particles. The clay is of similar composition to the older underlying estuarine muds, and is composed of mica, montmorillonite, chlorite, kaolinite and accessory minerals. The Holocene estuarine muds contain framboidal pyrite and exhibit a slight to strong hydrogen sulfide odor. The muds contain a fossil assemblage reflecting restricted to brackish water conditions. The muds are locally rooted. The maximum thickness of the estuarine muds is thought to be less than 40 m over drowned river valleys near San Francisco. Water salinity increased with time as the estuary grew in size and incoming freshwater from streams was progressively overshadowed by marine communication through the Golden Gate. For the last 7,500 years, the estuary has been slowly enlarging and fringing salt marshes have prograded.

Alluvial and fluvial sediments were deposited on the floodplains surrounding the bay as the base levels of streams rose in response to the expanding estuary. These older alluvial sediments are found to be interfingering and beneath a portion of the youngest estuarine muds.

As the estuary expanded and active alluvial sedimentation retreated, muds covered fringing sand sediments not destroyed by the erosion or transgressing shoreline processes. These alluvial sediments are described as fine- to coarse-grained, unconsolidated, moderately to poorly sorted sand and silt and coarse sand and gravel predominating in proximal fan and canyon environments. The sediments are often well-bedded and described as containing aboriginal artifacts and skeletal remains (Helley et al., 1979). Thickness varies, but the alluvial sediments are generally found to be less than 3 m thick. The thickness deposits (up to 15 m) are found at the heads of alluvial fans and in valley bottoms. The fine-grained alluvial sediments are deposited from standing flood waters which periodically inundated low-lying coastal marshes. The coarser-grained sediments were deposited by flowing water on active stream margins primarily during floods.

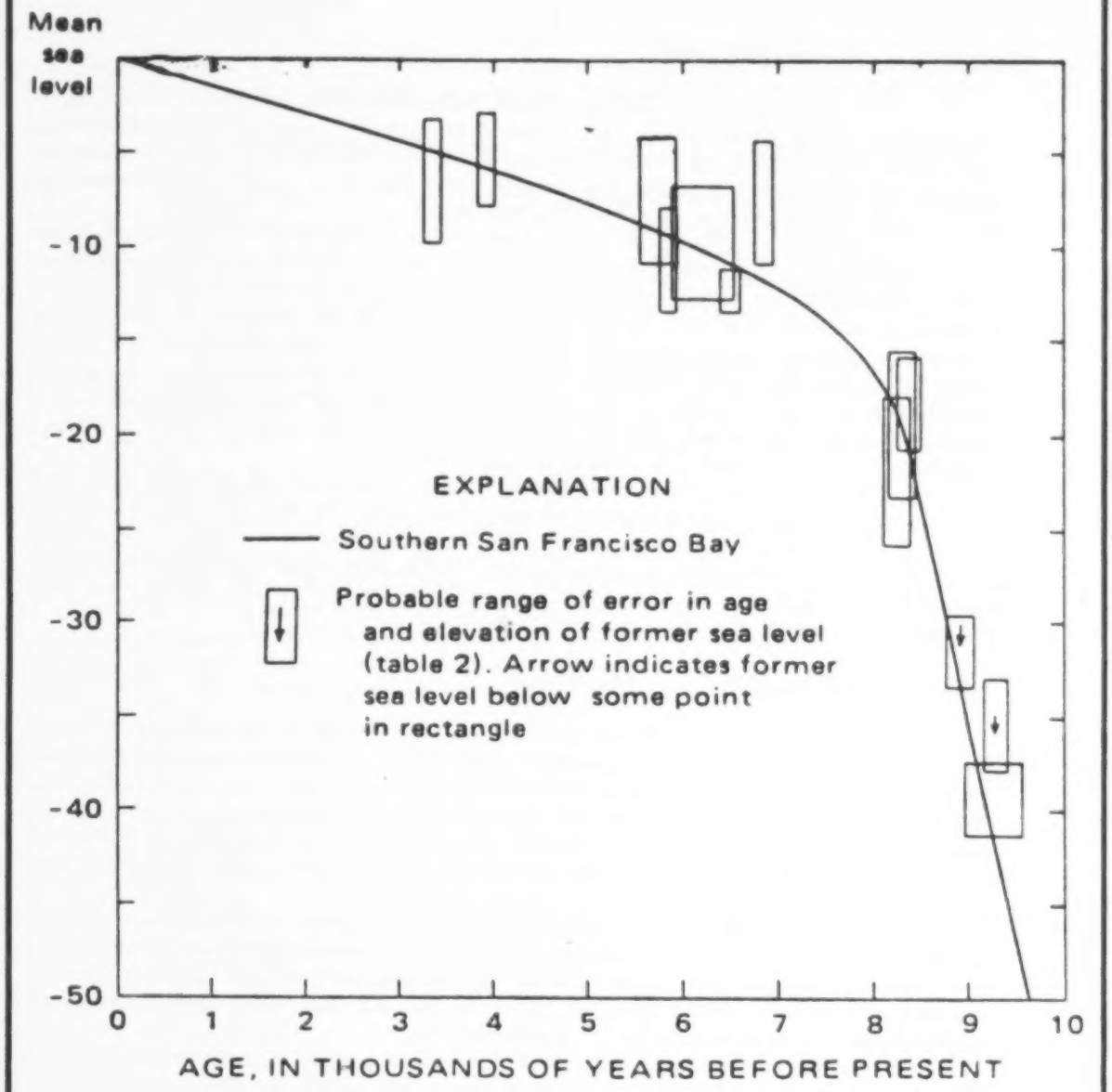


Figure II-21. Holocene Sea Level Curve in the Vicinity of Southern San Francisco Bay (modified from Atwater et al., 1976).

3.4.4 *Sea Level Fluctuations*

A generalized discussion of sea level fluctuations in the study area is included in Section 3.1.4. During glacial periods, the shoreline retreated to the vicinity of the Farallon Islands, draining the San Francisco Bay estuary. Extrapolation of sea level curves indicates the rising sea level entered the San Francisco Bay area through the Golden Gate 11,000 to 10,000 years ago (Helley et al. 1979; Atwater et al., 1976) (Figure II-21).

As noted in Section 3.4.2.2, as the modern estuary began to form, initial expansion occurred rapidly. During this initial period of estuarine development, freshwater fossil assemblages became dominated by brackish water to marine assemblages, indicating increasing salinity. Inundation proceeded at a rapid rate of up to 30 m/year along the course of the trunk stream draining the southern San Francisco Bay (Atwater et al., 1976). This early rapid sea level rise probably exceeded most local sedimentation rates, thereby limiting the formation of fringing tidal marshes before 7,500 years ago. As sea level rise slowed 7,500 to 5,000 years ago, the rate of estuarine enlargement slowed, and the rate of sedimentation in much of the area allowed progradation of fringing mud flats and salt marshes.

Since between 7,500 to 5,000 years ago, sea level rise in the greater San Francisco Bay area has averaged only 0.1 to 0.2 mm/year (Atwater et al., 1976). Helley et al. (1979) report that the active tectonic nature of the San Francisco Bay region suggests that the estuary is increasing in size through tectonic subsidence. Atwater et al. (1976) estimate late Pleistocene and Holocene tectonic subsidence as averaging between 0.2 and 0.4 mm/year in the San Francisco Bay area with the greatest amount of subsidence occurring to the south.

3.4.5 *Holocene Sediment Isopach Maps*

The majority of the Holocene thickness data presented in this section of the report was found in Goldman's (1969) geologic and engineering report on San Francisco Bay fill. Maps included in Goldman's reports present Younger Bay Mud thicknesses. This Younger Bay Mud represents much of the Holocene sediments in the San Francisco Bay area (see Section 3.4.3.3). Goldman (1969) acknowledges the U.S. Army Corps of Engineers, the U.S. Geologic Survey, and a number of private consulting firms for providing boring data from which these maps were constructed.

Starting to the northeast in Suisun/Grizzly Bay, Holocene sediments unevenly cover nearly the entire area. Maximum thickness exceeds 25 m, predominantly in deeper portions of the bay. Holocene sediments extend beyond shoreline, landward, particularly to the north. Much of the Holocene sediments found above the bay are alluvial and tidal marsh deposits. Holocene sediments up to 20 m thick occur in the Carquinez Strait.

Although thickness data are scarce in the central portion of San Pablo Bay, Holocene sediments appear to more evenly cover this portion of the greater San Francisco Bay region. Sediment thickness of greater than 25 m is reported in the northern half of San Pablo Bay. Alluvial and marsh sediments occur northward of the bay, defining stream valleys and sloughs.

North San Francisco Bay (north of Treasure Island) is characterized by an irregular cover of Younger Bay Muds. Holocene sediment thickness exceeds 40 m. Data are missing from the Golden Gate area. Holocene sediments fringe the shore of the west North Bay and extend more extensively landward on the east shores.

Younger Bay Muds unevenly cover the northern half of San Francisco Bay. Sediment thickness exceeds 40 m in places. The southern half of the South Bay (south of Hunters Point) is characterized by a more even and thinner Holocene cover, an average of 12 m thick. While

Holocene sediments only fringe the northern half of the South Bay, alluvial and marsh deposits extend far beyond the current shoreline in the southernmost portion of San Francisco Bay.

3.4.6 Specific Features Judged to Have the Greatest Potential for Prehistoric Occupation

Specific features judged to have the greatest potential for prehistoric occupation in the greater San Francisco Bay region are somewhat different in nature than those previously described along the ocean coast earlier in this report. The possibility of a barred coast (similar to that of the ocean coast) in the San Francisco Bay estuary is very unlikely. A partial list of features that may have acted as sites of occupation include: resistant headlands, islands, coastal and river plains, and terrestrial portions of sloughs and small bays.

Modern marine inundation of the San Francisco Bay region did not occur until at least 11,000 to 10,000 years ago. Prior to this marine incursion, the region was characterized as a structurally influenced, relatively low-relief river valley. Unlike the ocean coast where the great majority of marine transgression was of high energy and destructive in nature, the rising sea level of the greater San Francisco Bay region was far less destructive. The chance of cultural resource preservation is therefore much greater.

Unlike on the ocean coast, where features judged to have the greatest potential for prehistoric occupation were identified in energy shadows that allowed a relatively greater chance of preservation, the majority of the greater San Francisco Bay region is in a large energy shadow, the estuary. Rising sea levels in the estuary rather evenly affected shorelines throughout the bay area. Preservation could perhaps be best accomplished in a low-relief tidal/salt marsh environment where wave energy was low and sedimentation rates high.

Paleo-shoreline data are presented on the San Francisco paleo-landform maps.

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